I 19.42/4: 01-4170

REFERENCE
OVERFLOW

USGS
science for a changing world

Metal Loading in Soda Butte Creek Upstream of Yellowstone National Park, Montana and Wyoming: A Retrospective Analysis of Previous Research; and Quantification of Metal Loading, August 1999

Water-Resources Investigations Report 01-4170

KAN. CO. PUB. LIB.
FED. DEP. #0655
JAN 18 2002
RECEIVED

U.S. DEPARTMENT OF THE INTERIOR
U.S. GEOLOGICAL SURVEY

TD 427 .M44 B68 2001

BRIGHAM YOUNG UNIVERSITY

3 1197 22888 0545

Front cover photograph by Gregory K. Boughton.
Tributaries 100 feet upstream of Sheep Creek flowing into Soda Butte Creek.

U.S. Department of the Interior
U.S. Geological Survey

Metal Loading in Soda Butte Creek Upstream of Yellowstone National Park, Montana and Wyoming: A Retrospective Analysis of Previous Research; and Quantification of Metal Loading, August 1999

By Gregory K. Boughton

Water-Resources Investigations Report 01-4170

Prepared as part of the
NATIONAL WATER-QUALITY ASSESSMENT PROGRAM

Cheyenne, Wyoming
2001

U.S. Department of the Interior
Gale A. Norton, Secretary

U.S. Geological Survey
Charles G. Groat, Director

Any use of trade, product, or firm names in this publication is for descriptive purposes only and does not imply endorsement by the U.S. Government

For additional information write to:

District Chief
U.S. Geological Survey, WRD
2617 E. Lincolnway, Suite B
Cheyenne, Wyoming 82001-5662

Copies of this report can be purchased from:

U.S. Geological Survey
Branch of Information Services
Box 25286, Denver Federal Center
Denver, Colorado 80225

Information regarding the National Water-Quality Assessment (NAWQA) Program is available on the Internet via the World Wide Web. You may connect to the NAWQA Home Page using the Universal Resource Locator (URL):

<http://wwwrvares.er.usgs.gov/nawqa/nawqa_home.html>

UPB

CONTENTS

Page

Abstract 1
Introduction 2
Purpose and scope 2
Description of study area 2
Metal geochemistry 4
Acknowledgments 6
Retrospective analysis 6
Tracer-injection and synoptic-sampling study 8
Theory 8
Approach 8
Methods 9
Tracer injection and sampling 9
Synoptic sampling 10
Tracer-injection results 11
Downstream travel and dilution 11
Determination of discharge 11
Synoptic-sampling results 15
Inflows 15
Mainstem 15
Quantification of loads 20
Major ions 21
Metals 21
Metal sources 27
Summary 27
References cited 28
Appendix A--Annotated bibliography of previous research on metal loading in Soda Butte Creek, Montana and Wyoming 33
Appendix B--Field parameters and dissolved sulfate concentrations in synoptic samples from Soda Butte Creek and inflows, Montana and Wyoming, August 20, 1999 51
Appendix C--Dissolved and total-recoverable constituent concentrations in synoptic samples from Soda Butte Creek and inflows, Montana and Wyoming, August 20, 1999 55
Appendix D--Analysis of water samples collected at U.S. Geological Survey gaging station 06187915, water year 1999 63

Figures

1. Map showing location of the Soda Butte Creek study reach, and the McLaren Mine, tailings, and mill site, relative to Yellowstone National Park, Montana and Wyoming 3
2. Map showing location of transport sites and selected synoptic-sampling sites, Soda Butte Creek, Montana and Wyoming 5

3-12. Graphs showing:

3. Variation of dissolved bromide concentration with time at transport sites T1 and T2, Soda Butte Creek, Montana, August 1999 12
4. Variation of dissolved bromide concentration with time at transport sites T3 and T4, Soda Butte Creek, Montana and Wyoming, August 1999 13
5. Variation of dissolved bromide concentration with distance, Soda Butte Creek, Montana and Wyoming, August 20, 1999 14

Figures--Continued

Page

6. Discharge profile downstream from the injection site, Soda Butte Creek, Montana and Wyoming, August 20, 1999 14
7. Variation of stream and inflow pH with distance from the injection site, Soda Butte Creek, Montana and Wyoming, August 20, 1999 16
8. Variation of stream and inflow specific conductance with distance from the injection site, Soda Butte Creek, Montana and Wyoming, August 20, 1999 16
9. Variation of stream and inflow dissolved sulfate concentration with distance from the injection site, Soda Butte Creek, Montana and Wyoming, August 20, 1999 17
10. Variation of normalized total-recoverable concentrations of calcium, potassium, magnesium, and strontium with distance from the injection site, Soda Butte Creek, Montana and Wyoming, August 20, 1999 18
11. Variation of normalized total-recoverable concentrations of aluminum and silica with distance from the injection site, Soda Butte Creek, Montana and Wyoming, August 20, 1999 18
12. Variation of concentrations of dissolved and total-recoverable iron with distance from the injection site, Soda Butte Creek, Montana and Wyoming, August 20, 1999 19

13-21. Graphs showing sampled instream load, cumulative instream load, and cumulative inflow load of indicated constituents, Soda Butte Creek, Montana and Wyoming, August 20, 1999

13. Dissolved calcium 22
14. Dissolved silica 22
15. Dissolved sulfate 23
16. Dissolved iron 24
17. Total-recoverable iron 24
18. Dissolved aluminum 25
19. Total-recoverable aluminum 25
20. Dissolved manganese 26
21. Total-recoverable manganese 26

Tables

1. Sequence of tracer-injection sampling and activities in Soda Butte Creek, Montana and Wyoming, August 1999 10

CONVERSION FACTORS, ABBREVIATED WATER-QUALITY UNITS, AND ABBREVIATIONS

Multiply	By	To obtain
cubic feet per second (ft^3/s)	0.0283	cubic meters per second (m^3/s)
foot (ft)	0.3048	meter (m)
gallon (gal)	3.785	liter (L)
mile (mi)	1.609	kilometer (km)
pound (lb)	0.454	kilogram (kg)

Abbreviated water quality units and abbrevations used in this report:

g/L	grams per liter
L/s	liters per second
m	meter
mg/L	milligrams per liter
mg/s	milligrams per second
ml	milliliter
µm	micrometer
MRL	minimum reporting level
NAWQA	National Water-Quality Assessment Program
NPS	National Park Service
USEPA	U.S. Environmental Protection Agency
USGS	U.S. Geological Survey
YNP	Yellowstone National Park

Digitized by the Internet Archive
in 2013

http://archive.org/details/metalloadinginso00boug

Metal Loading in Soda Butte Creek Upstream of Yellowstone National Park, Montana and Wyoming: A Retrospective Analysis of Previous Research; and Quantification of Metal Loading, August 1999

By Gregory K. Boughton

ABSTRACT

Acid drainage from historic mining activities has affected the water quality and aquatic biota of Soda Butte Creek upstream of Yellowstone National Park. Numerous investigations focusing on metals contamination have been conducted in the Soda Butte Creek basin, but interpretations of how metals contamination is currently impacting Soda Butte Creek differ greatly. A retrospective analysis of previous research on metal loading in Soda Butte Creek was completed to provide summaries of studies pertinent to metal loading in Soda Butte Creek and to identify data gaps warranting further investigation.

Identification and quantification of the sources of metal loading to Soda Butte Creek was recognized as a significant data gap. The McLaren Mine tailings impoundment and mill site has long been identified as a source of metals but its contribution relative to the total metal load entering Yellowstone National Park was unknown. A tracer-injection and synoptic-sampling study was designed to determine metal loads upstream of Yellowstone National Park.

A tracer-injection and synoptic-sampling study was conducted on an 8,511-meter reach of Soda Butte Creek from upstream of the McLaren Mine tailings impoundment and mill site downstream to the Yellowstone National Park boundary in August 1999. Synoptic-sampling sites were selected to divide the creek into discrete segments. A lithium bromide tracer was injected continuously into Soda Butte Creek for 24.5 hours. Downstream dilution of the tracer and current-meter measurements were used to calculate the stream discharge. Stream discharge values, combined with constituent concentrations obtained by synoptic sampling, were used to quantify constituent loading in each segment of Soda Butte Creek.

Loads were calculated for dissolved calcium, silica, and sulfate, as well as for dissolved and total-recoverable iron, aluminum, and manganese. Loads were not calculated for cadmium, copper, lead, and zinc because these elements were infrequently detected in mainstem synoptic samples. All of these elements were detected at high concentrations in the seeps draining the McLaren Mine tailings impoundment. The lack of detection of these elements in the downstream mainstem synoptic samples is probably because of sorption (coprecipitation and adsorption) to metal colloids in the stream.

Most of the metal load that entered Soda Butte Creek was contributed by the inflows draining the McLaren Mine tailings impoundment (between 505 meters and 760 meters downstream from the tracer-injection site), Republic Creek (1,859 meters), and Unnamed Tributary (8,267 meters). Results indicate that treatment or removal of the McLaren Mine tailings impoundment would greatly reduce metal loading in Soda Butte Creek upstream of Yellowstone National Park. However, removing only that single source may not reduce metal loads to acceptable levels. The sources of metal loading in Republic Creek and Unnamed Tributary merit further investigation.

INTRODUCTION

The Soda Butte Creek basin drains a mineralized area, the New World Mining District, which has been the site of historic mining activities (fig. 1). Soda Butte Creek is the only stream flowing into Yellowstone National Park (YNP) that has been significantly impacted by mining activities. Metal loading to the creek has negatively impacted water quality and the aquatic biota. Sediments from the McLaren Mine tailings impoundment have been found to contain high concentrations of trace elements (Epstein, 1997).

Floods are perhaps the most serious risk to aquatic life in Soda Butte Creek. A flood in 1950 breached the dam at the McLaren Mine tailings impoundment and mobilized tailings that have been found more than 24.9 kilometers downstream, just above the confluence of Soda Butte Creek and the Lamar River (Meyer, 1993). Over the years, the sediments from the tailings are being reworked and transported through the system (Marcus and others, 1995). A study of geomorphic processes controlling movement of contaminated sediments indicated that mine impacts will persist for centuries in Soda Butte Creek (Marcus and others, 2001). Flooding could expose buried tailings sediments, bring fresh tailings sediments into Soda Butte Creek, or carry metal-contaminated invertebrates into YNP.

Numerous investigations focusing on metals contamination have been conducted in the Soda Butte Creek basin. Conclusions reached by investigators on how metal loading continues to affect Soda Butte Creek differ greatly. Research related to the water quality of the creek indicated that the mine tailings along Soda Butte Creek upstream from Cooke City, appear to have no effect on the water chemistry of Soda Butte Creek (Miller and others, 1997). A study of the floodplain grasslands community clearly showed the impacts of past tailings releases (Stoughton, 1995). Researchers studying the aquatic biota concluded that the creek is being adversely affected by the McLaren Mine tailings at certain times of the year (Nimmo and Willox, 1996). The lack of consensus on whether metals continue to negatively impact Soda Butte Creek highlights the need for further compilation of research and further investigation. The National Park Service (NPS) has expressed concern that the runoff and ground water at the McLaren Mine tailings impoundment and mill site appear to be continuing sources of metals entering Soda Butte Creek (Roy Irwin, National Park Service, written commun., 1998). This project was funded through the National Park Service - U.S. Geological Survey, Water Quality Assessment and Monitoring Partnership to investigate metal loading in Soda Butte Creek upstream of YNP.

Purpose and Scope

This report has two principal objectives. The first objective is to provide a retrospective analysis of previous research on metal loading in Soda Butte Creek. This was accomplished by compiling and organizing existing publications and data. A computerized literature search was conducted to identify relevant publications. Journal articles, published reports and books, unpublished master's theses, conference proceedings, and past and current research projects are referenced. For some bibliographic citations, abstracts have been provided.

The second objective is to identify and quantify sources of metal loads in the Soda Butte Creek basin upstream of YNP. This was achieved through a study combining tracer injection and synoptic sampling. Metal loads in the mainstem were quantified using stream discharge determined by tracer-injection methods and current-meter measurements, and metal concentrations determined from analyses of synoptic samples. Downstream profiles of metal loads were constructed to identify and quantify principal sources of metal loads to Soda Butte Creek. This report includes both the retrospective analysis and detailed results of the tracer-injection and synoptic-sampling study.

Description of Study Area

The study area is in the New World Mining District (District). The District, which includes a mixture of National Forest and private lands, is located in the general vicinity of Cooke City, Montana and contains hard rock mining wastes and acid discharges that may impact the environment. Human health and environmental issues in the area are related to elevated levels of heavy metals present in mine waste piles, open pits, acidic water discharging from mine openings, and stream sediments (Maxim Technologies, 1999).

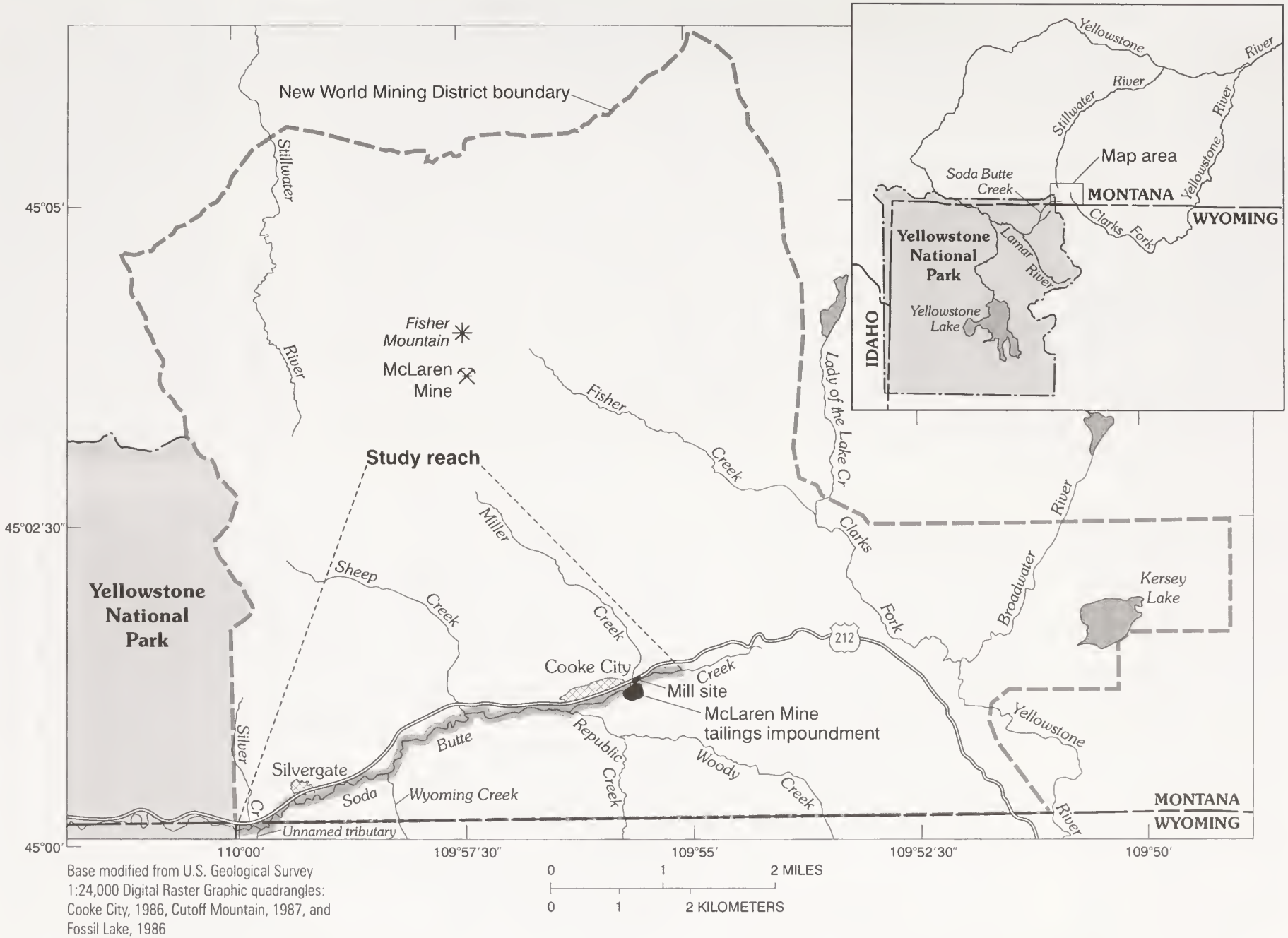


Figure 1. Location of the Soda Butte Creek study reach, and the McLaren Mine, tailings, and mill site, relative to Yellowstone National Park, Montana and Wyoming.

The District is situated at the headwaters of three river basins, which all eventually flow into the Yellowstone River. The three streams are the Clarks Fork Yellowstone River, the Stillwater River, and Soda Butte Creek. Soda Butte Creek is a tributary of the Lamar River, with their confluence in YNP. The major tributaries of Soda Butte Creek are Miller, Republic, Sheep, Wyoming, and Silver Creeks and an Unnamed Tributary.

Soda Butte Creek originates northeast of Cooke City, Montana and flows approximately 8.5 river kilometers before crossing the northeast corner of YNP. The basin upstream of the YNP boundary has been the site of numerous historic mining operations. Although the impacts of mining are documented, differentiating between natural and human-induced sources of metals is extremely difficult because the geologic units in the watershed are highly mineralized. A description of the local geology follows [Montana Bureau of Mines and Geology, 1999, p. 7-8].

> Bedrock in the upper Soda Butte Creek drainage consists of Precambrian metamorphic, Paleozoic sedimentary, and Eocene volcanic rock. The eastern, upstream portion of the watershed is predominantly Precambrian granitic gneiss with slightly younger gabbro and dolerite dike intrusions and small plutons that were later metamorphosed. This crystalline rock is well exposed in the Colter Pass area but obscured elsewhere by glacial deposits. Outcrops have been mapped as far downstream as Cooke City. In the Cooke City area, younger, sedimentary rock overlies the crystalline rocks.
>
> During the Paleozoic Era, a thick sequence of sedimentary rock was deposited unconformably on a gently sloping erosional surface of Precambrian rock. Exposed sedimentary rock is predominantly Cambrian and includes the Flathead Sandstone, the Wolsey and Park Shales, and the Meagher and Pilgrim Limestones. The Pilgrim Limestone forms the spectacular cliffs on the south side of the valley between Cooke City and Silver Gate. Cambrian rock is overlain unconformably by Ordovician Bighorn Dolomite, which is overlain unconformably by the Devonian Jefferson and Three Forks Formations and the Mississippian Madison Limestone.
>
> The Absaroka volcanic field became active in the Eocene Epoch and deposited the andesitic volcaniclastic rock and flows of the Lamar River Formation unconformably on the Madison Limestone.

Ore from the McLaren Mine, a gold, silver, and copper mine active from 1933 to 1953, was processed at a mill located next to Soda Butte Creek, 4 miles upstream from the YNP boundary (Glidden, 1982). Gold, silver, and copper were leached out with cyanide. During the period the mill was operational, approximately 150,000 cubic yards of tailings were deposited on the valley floor of Soda Butte Creek, which originally meandered through the area currently overlain by the tailings (fig. 2). Tailings accumulated during the mine's operation were placed directly instream covering an oxbow of Soda Butte Creek (Bureau of Reclamation, 1989).

In June of 1950, heavy rainstorms and flash flooding in the upper Soda Butte Creek basin breached the dam at the McLaren Mine tailings impoundment, spilling a large amount of the tailings into Soda Butte Creek. In 1969, the creek was rerouted around the north edge of the impoundment. The tailings were leveled, graded, covered with a 0.5-1.5 meter (m) thickness of alluvial sand and gravel, and seeded with grass (U.S. Environmental Protection Agency, 1972; Knudson and Estes, 1975). In 1989, the U.S. Environmental Protection Agency (USEPA) and Kennecott Corporation installed a buttress berm to reinforce the tailings dam and removed some of the tailings below the dam (U.S. Environmental Protection Agency, 1989). Despite these efforts, the banks and bed of Soda Butte Creek around and downstream from the tailings are continuously stained by ground- and surface-water seeps and drains (Nimmo and Willox, 1996).

Metal Geochemistry

Metals may be derived from the weathering of rocks or, increasingly, they may be introduced into the atmosphere and hydrosphere by human activities. Mining activities can result in release of metals (Drever, 1997). Acid mine drainage results from the oxidation of sulfide minerals exposed during mining, which produces sulfuric acid and sulfate salts. The acid dissolves minerals in the rocks, further degrading the quality of the drainage water (Bates and Jackson,

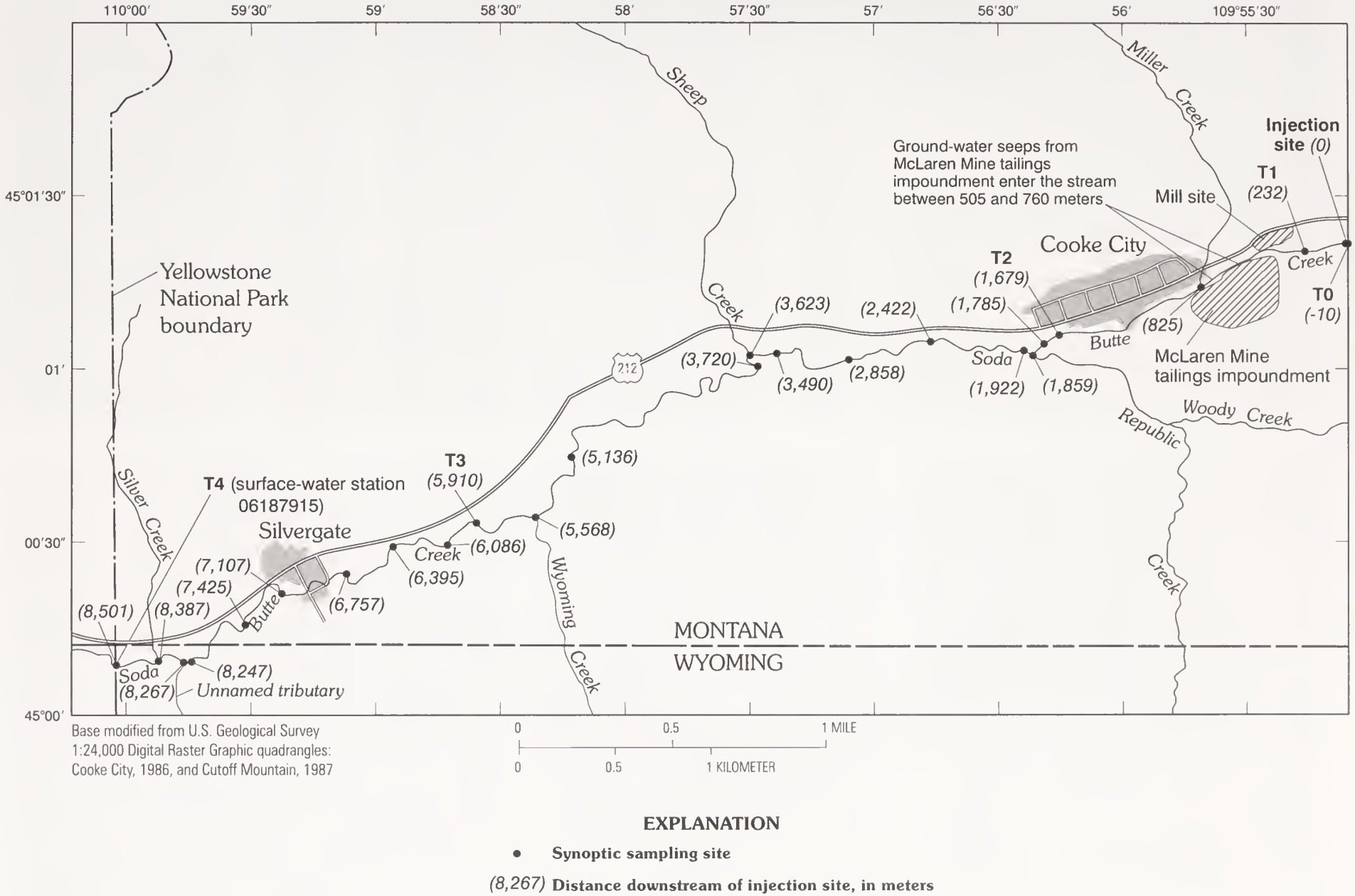


Figure 2. Location of transport sites and selected synoptic-sampling sites, Soda Butte Creek, Montana and Wyoming.

1980). The contaminated water is often an ochre color indicating high levels of iron and may have the smell of rotten eggs from the presence of hydrogen sulfide.

Mixing of waters of widely different pH may have significant chemical and biological consequences. Examples of pH-mixing effects were observed by Theobald and others (1963) and McKnight and Feder (1984) at the confluence of a low-pH stream with a neutral-pH stream. When the pH of the water increased, the dissolved and colloidal metals precipitated out of solution. The acidic waters carried relatively high concentrations of aluminum, iron, zinc, and other metals, and the precipitation of these metals as hydrous oxides below the confluence limited the abundance of periphyton and benthic invertebrates (Elder, 1988).

A similar situation is observed in Soda Butte Creek where acidic ground water inflows from the McLaren Mine tailings impoundment enter the creek. The ground water contains high concentrations of dissolved metals. The stream reach immediately downstream of the acidic inflows is coated with ochre-colored deposits typical of streams receiving acid mine drainage. These deposits, consisting mainly of ferric hydroxides, form as the reduced ground water becomes oxidized because of aeration and the pH rises because of mixing with the neutral-pH surface waters. Adverse effects of these deposits on the aquatic biota of Soda Butte Creek have been documented (Nimmo and Willox, 1996).

When metal-rich, acidic mine drainage enters streams with near-neutral pH, colloidal solids form. Colloids are solids that range in size from about 0.001 to 1 micrometer (μm)—intermediate between that of dissolved molecules and that of particles that can settle out of solution. Collodial particles are electrically charged. The charge may originate in two ways: (1) adsorption of ions from the liquid, or (2) by the direct ionization of the material of the particle (Mason, 1966). Colloids tend to aggregate and eventually settle from the water. The mostly ferric hydroxide colloidal solids have a large capacity to sorb metals.

Acknowledgments

Many agencies and organizations provided publication lists and abstracts that were used to produce the annotated bibliography. The author thanks the Federal and State agencies, private organizations, and individual researchers for their cooperation in providing information for this report.

The tracer-injection and synoptic-sampling study required long hours and could not have been accomplished without the dedicated participation of the field team members. The author thanks Robert Broshears, Briant Kimball, Robert Runkel, Myron Brooks, Melanie Clark, Joe Pohl, Glen Laidlaw, Dev Niyogi, and Fred Rossi of the U.S. Geological Survey (USGS); and volunteers Ben Kimball (USGS) and Katie Randall (Yellowstone Ecosystem Studies). Linda Gerner and Chump Bailey of the USGS performed the laboratory analyses. Robert Broshears and Briant Kimball also provided invaluable assistance in interpreting the data.

RETROSPECTIVE ANALYSIS

This section of the report provides a retrospective analysis of previous research relating to metal loading in Soda Butte Creek. Existing publications and data were compiled and organized to accomplish this task. A computerized literature search was conducted to identify relevant publications. Journal articles, published reports and books, unpublished students' theses, conference proceedings, and research projects are referenced.

A computerized literature search for investigations relating to metals contamination in Soda Butte Creek was conducted using several scientific databases, Internet search engines, and Washington State University Library's Scientific Research in Yellowstone National Park online database (*http://www.wsulibs.wsu.edu/ris/risweb.isa*). To supplement the computerized retrieval, State and Federal agencies, private organizations, and individual researchers supplied information that might not have been cited otherwise.

The complete bibliography is presented in appendix A. References are listed alphabetically by principal author, either individual or corporate. Every effort has been made to ensure that all references in this bibliography are correct but not all references could be checked or verified. For some bibliographic citations, abstracts or other brief descriptions have been provided. References to research projects list the objective of the project and the findings and status, if any.

None of the studies conducted on Soda Butte Creek have included an examination of the effects of metal loading on the entire watershed. With this in mind, the research can be divided into studies of surface-water quality, fluvial geomorphology, and aquatic biota.

The many studies of the surface-water quality of Soda Butte Creek have reached differing conclusions on the extent of water-quality degradation. Detailed water analyses carried out by Mills and Sharpe (1968) revealed no materials considered toxic to fish or aquatic invertebrates. Hill (1970) measured a decrease in pH and alkalinity and an increase in conductivity, hardness, and concentrations of sulfate, iron, manganese, zinc, and copper downstream of the McLaren Mine tailings impoundment relative to a site upstream of the tailings. Studies carried out by Chadwick (1974), David Stiller and Associates (1983), Ecology and Environment, Inc. (1988) concluded that the primary water-quality problem was dissolved iron concentrations that were toxic to aquatic life. Forstner and Wittman (1983) determined that copper was the most toxic of the metals found in the surface water. INTERA, Inc. (1991) concluded that the "dam stabilization" completed by Kennecott Corporation in 1990 was preventing any further discharges of tailings material into the creek and water quality was improving. The Bureau of Reclamation (1991) collected one sample that exceeded the aquatic-life criterion for copper, although iron was the only element to show consistently higher concentrations below the mine tailings compared to the concentrations above the tailings. Miller and others (1997) concluded that there was little to no effect on the water quality of Soda Butte Creek from the presence of mine workings or tailings upstream from Cooke City during the fall of 1996.

Most fluvial geomorphology investigators have concentrated on evaluating the mine tailings washed into the creek when the dam at the McLaren Mine tailings impoundment failed in the summer of 1950, resulting in deposition of about 3.1×10^4 cubic meters of tailings along the floodplain (Meyer and Watt, 1998). Deposits of the tailings from the 1950 flood have been found more than 24.9 kilometers downstream, just upstream from the confluence of Soda Butte Creek and the Lamar River (Meyer, 1993). Over the years, the sediments from the tailings are being reworked and transported through the system (Marcus and others, 1995). Ladd (1995) found that channel morphology controls the spatial distribution of trace metals in the bed sediments of the creek. The USGS determined that a 100-year flood would cause substantial flooding of the tailings impoundment (Omang and others, 1983). In 1996, flooding caused the deposition of overbank sediments up to a few decimeters below the highest tailings deposits (Stephen V. Lynn, U.S. Geological Survey, written commun., 1997). Recent studies have taken advantage of advances in multispectral digital imaging to map hydrogeomorphic stream units in Soda Butte Creek (Ewing, 1994; Wright, 1998). Marcus and others (2001) examined geomorphic processes controlling movement of contaminated sediments and concluded that mine impacts will persist for centuries in Soda Butte Creek.

Most of the research conducted on metal loading in Soda Butte Creek has focused on the aquatic biota. A decrease in the types and numbers of bottom organisms was observed in the vicinity of the McLaren Mine tailings on Soda Butte Creek outside of the YNP boundary (U.S. Environmental Protection Agency, 1971). Duff (1972) concluded that runoff and seepage from the McLaren Mine tailings to Soda Butte Creek were adversely impacting the creek ecosystem and no fish were present from the tailings site downstream for 3 miles. Pickett and Chadwick (1972) determined that seepage from the mill tailings at Cooke City was adversely affecting the water quality of Soda Butte Creek and that the natural flora and fauna present above the tailings were either eliminated or severely reduced immediately below the tailings. Riparian vegetation (grass, horsetail, and willow) showed greater concentrations of copper, lead, and zinc immediately downstream of the tailings than upstream, with concentrations decreasing downstream towards the YNP boundary (Erickson and Norton, 1994). Pollution effects, though severe immediately downstream from the tailings, have been reduced in recent years as the result of efforts to better contain the tailings and prevent seepage of acidic waters (Mahoney, 1996). Macroinvertebrate populations generally increase in number and diversity with increasing distance downstream from Cooke City (Marcus, 1997). Nimmo and others (1998) concluded that aquatic resources in Soda Butte Creek within YNP continue to be threatened by heavy metals from historical mining and milling activities upstream of the YNP boundary. Toxicity tests, using surrogate test species, and analyses of metals in water, sediments, and macroinvertebrate tissues sug-

gested that copper is the metal of concern in the watershed (Nimmo and others, 1998).

In general, studies of the aquatic biota indicate that Soda Butte Creek continues to be negatively impacted by historic mining activities. Flooding could worsen the impacts by exposing buried tailings sediments, washing fresh tailings sediments into Soda Butte Creek, or carrying metal-contaminated aquatic biota into YNP. Such an incident probably would increase the metal loading in Soda Butte Creek.

Numerous researchers have studied metal loading of Soda Butte Creek for short time periods, generally only one season of the year. Their conclusions on the effects of metal loading on the aquatic ecosystem vary widely. Spring snowmelt and summer thunderstorms probably contribute a significant percentage of the annual metal loading. During initial stages of storm runoff, there is a significant increase of the metal concentrations in solution. A system this dynamic requires monitoring for multiple years with an emphasis on event sampling. A National Water-Quality Assessment Program (NAWQA) sampling site on Soda Butte Creek at the YNP boundary will follow this schedule during 2000-2001, but the large dilution effect of numerous downstream tributaries may mask the effects of increased metal loading at upstream locations.

The most obvious gap in the existing data is a lack of knowledge of the sources contributing to the metal loads in Soda Butte Creek. The McLaren Mine tailings impoundment and mill site has long been identified as a source of metals but its contribution relative to the total metal load entering YNP is unknown. Other unidentified sources may contribute to the metal load of the creek. The tracer-injection and synoptic-sampling study discussed next was designed to identify and quantify sources of metal loading in Soda Butte Creek upstream of YNP.

TRACER-INJECTION AND SYNOPTIC-SAMPLING STUDY

Constituent load profiles along a stream reach can be constructed using stream discharge (derived from tracer injection) and constituent concentrations (measured in water-quality samples). A tracer-injection and synoptic-sampling study was conducted on Soda Butte Creek in August 1999.

Theory

Discharge in mountain streams can be measured precisely by adding a dye or salt tracer at a constant rate to a stream, measuring the dilution of the tracer as it moves downstream, and calculating discharge from the amount of dilution (Kimball, 1996). Marchand and others (1984) indicate that conventional current-meter measurements of discharge do not adequately account for hydraulic conditions present in high-gradient, shallow-depth streams common to mountainous regions. This is because flow is over and around cobbles, resulting in rapid changes in direction and unsteady velocity distributions, which make the assumptions of conventional measurements inappropriate. Also, in cobble-bed mountain streams there may be significant flow of "streamwater" through the streambed (hyporheic flow) (Bencala, 1984). Such flow is contributing to the transport of solutes; however, conventional current-meter measurements do not register this flow component (Zellweger and others, 1989).

When a tracer is injected continuously, at some point downstream the tracer becomes completely mixed throughout the cross section of flow and reaches a plateau concentration. For some additional distance downstream from this point the plateau concentration is approximately the same at any point in the stream (Wilson and Rankl, 1996, p. 18). The tracer is maintained at a plateau concentration in the stream while water samples are collected synoptically (at many sites during a short period of time). The samples are analyzed for constituent concentrations. Instantaneous constituent loads, in milligrams per second (mg/s), are calculated by multiplying the discharge, in liters per second (L/s), by the constituent concentrations, in milligrams per liter (mg/L). Constituent-loading profiles indicate which segments of the stream are receiving significant constituent loading. Tracer-injection and synoptic-sampling studies that determined metal loading from abandoned mine lands similar to that conducted on Soda Butte Creek are described in Broshears and others (1993) and Kimball (1996).

Approach

A tracer-injection and synoptic-sampling study was conducted in August 1999 to identify and quantify sources of metal loading in Soda Butte Creek. The

study area encompassed an 8,511-m reach of Soda Butte Creek from upstream of the McLaren Mine tailings impoundment and mill site downstream to the YNP boundary (fig. 2). The basic tracer-injection methods followed those established by the USGS (Kilpatrick and Cobb, 1985) with the exception that lithium bromide was used as the tracer instead of a fluorescent dye.

Methods

Before injection of the tracer, a field reconnaissance was conducted to determine the optimal location of the tracer-injection and synoptic-sampling sites. Specific conductance, pH, water temperature, and global positioning system coordinates were recorded at each potential sampling site. Synoptic sampling sites along Soda Butte Creek were located to bracket the major visible inflows and mining-related features. Supplementary synoptic sampling sites were located in sections of the creek without any visible inflows, allowing for the identification and quantification of any substantial subsurface inflows. The stream reach was divided into 46 segments for synoptic sampling. In addition, 28 inflows were sampled to determine the quality of water entering the creek. Sampling sites were identified by their distance downstream of the injection site, in meters. For example, site 505 m is 505 meters downstream of the injection site. Synoptic-sampling site descriptions, field parameters, and sulfate concentrations are given in appendix B.

Automatic samplers were installed and operated at four transport locations (T1, T2, T3, and T4) downstream of the injection site prior to injection. Samples were collected periodically at these four sites, including the entire duration of the synoptic-sampling event, to observe the arrival and departure of the tracer and to quantify the tracer plateau concentration.

Tracer Injection and Sampling

During a 2-day period in August 1999, a tracer solution containing lithium bromide was injected continuously at the injection site (0 m) at a constant rate. The injection site was located upgradient of any influence from the McLaren Mine tailings. Setup at the site required mixing the lithium bromide tracer with stream water to produce a near-saturated solution. It required about 270 kilograms of lithium bromide to bring the bromide concentration in the stream up to the grams per liter (g/L) range - a concentration that is easily detectable but not harmful to the aquatic biota or humans. The tracer solution was injected continuously into Soda Butte Creek at a rate of 550 milliliters per minute for 24.5 hours. Six samples of the tracer solution were collected periodically during the injection period to document the tracer concentration. The bromide concentration ranged from 129.4 g/L to 114.0 g/L; the median bromide concentration (118.5 g/L) was used for calculating streamflow.

Ideal concentration profiles of an injected tracer over time have three distinct regions that show the arrival, plateau (or equilibrium) conditions, and departure of the tracer. Arrival time is defined as the time in which the tracer reaches a concentration midway between the ambient (background) tracer concentration and the plateau concentration (Zellweger and others, 1988). A stable plateau concentration usually exists until the tracer injection is terminated. The departure of the tracer begins when the tracer injection is terminated and tracer concentrations decrease from plateau to ambient concentrations. Data from the transport sites are used to verify that a stable plateau concentration was reached at each site.

The samples were filtered, using 0.45-μm capsule filters, into 125-milliliter (ml) bottles. Filters were rinsed with 250 ml of new sample before filling of the 125-ml bottle. Samples were analyzed for lithium and bromide.

Lithium and bromide tracer concentrations and sulfate concentrations were analyzed at the USGS Utah District laboratory in Salt Lake City using a Dionex 20021 ion chromatograph with an AS4A column, an AG4A guard, and a conductivity detector. Analytical procedures followed by the Utah District laboratory are outlined by Brinton and others (1996).

Discharge was measured prior to injection at the four downstream transport sites (T1-T4, fig. 2), including the downstream end of the study reach, using standard current-meter methods (Rantz and others, 1982a, 1982b). This information was used to calculate the amount of tracer to be injected into Soda Butte Creek. The discharge measurements were also used to check the accuracy of the discharge values calculated using the tracer concentrations.

Synoptic Sampling

Synoptic sampling provides a view of the changes along a stream at a given point in time. Synoptic sites were to be sampled when the tracer reached plateau concentration along the entire study reach. Synoptic sampling was conducted in three separate phases. Synoptic samples were collected in upstream order from 1,679 m to -10 m; 5,910 m to 1,785 m; and 8,501 m to 6,086 m in an attempt to ensure that all samples were collected while the tracer was at plateau concentration. There were 75 synoptic-sampling sites for this study—47 mainstem sites and 28 inflow sites. For the sake of clarity, the sequence of events is listed in table 1.

Water samples for major ion and metal analysis were collected in acid-washed polyethylene bottles at all synoptic-sampling sites. Water samples were collected using equal-width increment sampling methods with a DH-81 depth-integrating sampler. The samples were composited in 2-liter plastic jugs for separation into the various bottles. Temperature was measured at the time of collection and recorded along with field notes about the sampling conditions and any important observations. Samples were placed in dark bags to keep them out of direct sunlight and prevent photoreduction of iron in the samples.

Samples were processed at a temporary field laboratory. Splits of each sample were prepared for different analyses. Filtration using 0.45-μm in-line capsule filters provided an operational definition of dissolved metal concentrations, not a truly dissolved metal concentration (Kimball and others, 1995). Some colloidal-sized particles probably passed through the 0.45-μm filters, increasing the metals concentrations.

Sample analyses included pH and specific conductance (sample water was unfiltered and untreated); dissolved concentrations of lithium, bromide, and sulfate (sample water was filtered and untreated); and dissolved (sample water was filtered and acidified) and total-recoverable (sample water was unfiltered and acidified) concentrations of aluminum, arsenic, calcium, cadmium, copper, iron, potassium, magnesium, manganese, sodium, nickel, lead, silica, strontium, and zinc.

Trace-element concentrations were determined at the USGS laboratory in Golden, Colorado. Samples were analyzed for dissolved trace elements by inductively coupled plasma-atomic emission spectroscopy (ICP-AES). Samples were analyzed for total-recoverable trace elements by ICP-AES with standard USEPA digestion for total-recoverable concentrations.

Table 1. *Sequence of tracer-injection sampling and activities in Soda Butte Creek, Montana and Wyoming, August 1999*

[m, meters downstream of injection site]

Date	Time	Activity
8/17/99	1000	Reconnaissance of stream and inflows to determine locations of sampling sites and to measure downstream distances from the injection site.
8/18/99	0800	Reconnaissance of stream and inflows to determine locations of sampling sites and to measure downstream distances from the injection site.
	1500	Installation of automatic samplers at the four downstream transport sites, T1-T4.
8/19/99	1235	Current-meter discharge measurements at the four downstream transport sites.
	1400	Start of continuous injection of lithium bromide tracer (0 m).
	1430	Start of sampling for the tracer arrival at downstream transport sites.
8/20/99	0836	Synoptic sampling of stream and inflow sites. Samples collected in upstream order from 1,679 m to -10 m.
	1320	Synoptic sampling of stream and inflow sites. Collected in upstream order from 5,910 m to 1,785 m.
	1430	End of tracer injection. Start of sampling for the tracer departure at the four downstream transport sites.
	1725	Synoptic sampling of stream and inflow sites. Collected in upstream order from 8,501 m to 6,086 m.
8/21/99		Continued sampling with automatic samplers at transport sites T3 and T4.
	1200	End of sampling at transport sites T3 and T4.

A detailed description of laboratory analytical and quality assurance procedures can be found in Kimball and others (1999).

Tracer-Injection Results

Accurate discharge values are essential for calculating loads. Injecting a tracer to calculate discharge is advantageous to current-meter methods for two reasons: (1) synoptic samples for determination of discharge can be collected more quickly than current-meter measurements can be conducted, and (2) tracer-injection methods account for the hyporheic flow that cannot be measured by current-meter methods.

Downstream Travel and Dilution

Movement of the tracer was monitored at four downstream transport sites (T1-T4) (fig. 2). Site T1 (232 m) was located close to the injection site (0 m) to minimize the potential for inflows to increase the discharge between the sites, but far enough downstream for the tracer solution to completely mix with the stream. Sites T2 (1,679 m), T3 (5,910 m), and T4 (8,501 m) were located further downstream to monitor the tracer over the entire study reach.

Lithium concentrations were too low to be of use in calculating discharge. The variation of dissolved bromide tracer concentration with time at transport sites T1 and T2 is shown in figure 3; and at sites T3 and T4 in figure 4. A smoothed line is plotted on the figures. The smoothed line uses medians to summarize consecutive overlapping segments of the sequence (Velleman and Hoaglin, 1981).

Synoptic sampling began about 19 hours after the start of tracer injection to allow the tracer to reach plateau concentration in the study reach. The synoptic-sampling periods are shaded on figures 3 and 4.

The variation of dissolved bromide concentration with distance is shown in figure 5. Bromide concentration decreases downstream because of dilution from surface and subsurface inflows. Significant decreases occur below the confluences with Miller Creek (825 m) and Republic Creek (1,859 m).

Tracer concentrations were to be used to calculate the stream discharge along the entire study reach. Because of unexpected problems with the tracer, it was not possible to accurately calculate the discharge downstream of 1,785 m using tracer concentrations. It is possible that the tracer was not injected for a sufficient time to completely mix in the hyporheic zone because Soda Butte Creek has a wide alluvial valley. The discharge values measured by current-meter methods at T3 and T4 were used to determine the constituent loads downstream of 1,785 m. A detailed description of how this was accomplished is provided in the following section.

Determination of Discharge

Lithium and bromide were not detected in any background or inflow samples. This simplified the discharge calculations and is one advantage of using lithium bromide as a tracer rather than a less expensive compound such as sodium chloride. With the injection rate, injectate concentration, and downstream concentration of the tracer in the stream known, stream discharge at the first sampling site downstream from the injection site is calculated using the equation:

$$Q_A = Q_{inj} C_{inj} / C_A \text{ (modified from Kimball and others, 1999, p. 4)} \quad (1)$$

where Q_A is the stream discharge at the first downstream site,

Q_{inj} is the rate of the tracer injection into the stream,

C_{inj} is the injectate concentration, and

C_A is the tracer concentration at the first site downstream from the tracer injection.

The discharge at the first site downstream from the injection site, Q_A, is used to calculate the discharge at the next downstream site, and each subsequent sampling site by using the equation:

$$Q_B = Q_A C_A / C_B \text{ (modified from Kimball and others, 1999, p. 4)} \quad (2)$$

where Q_B is the discharge at the downstream site,

Q_A is the upstream discharge,

C_A is the upstream tracer concentration, and

C_B is the tracer concentration at the downstream site.

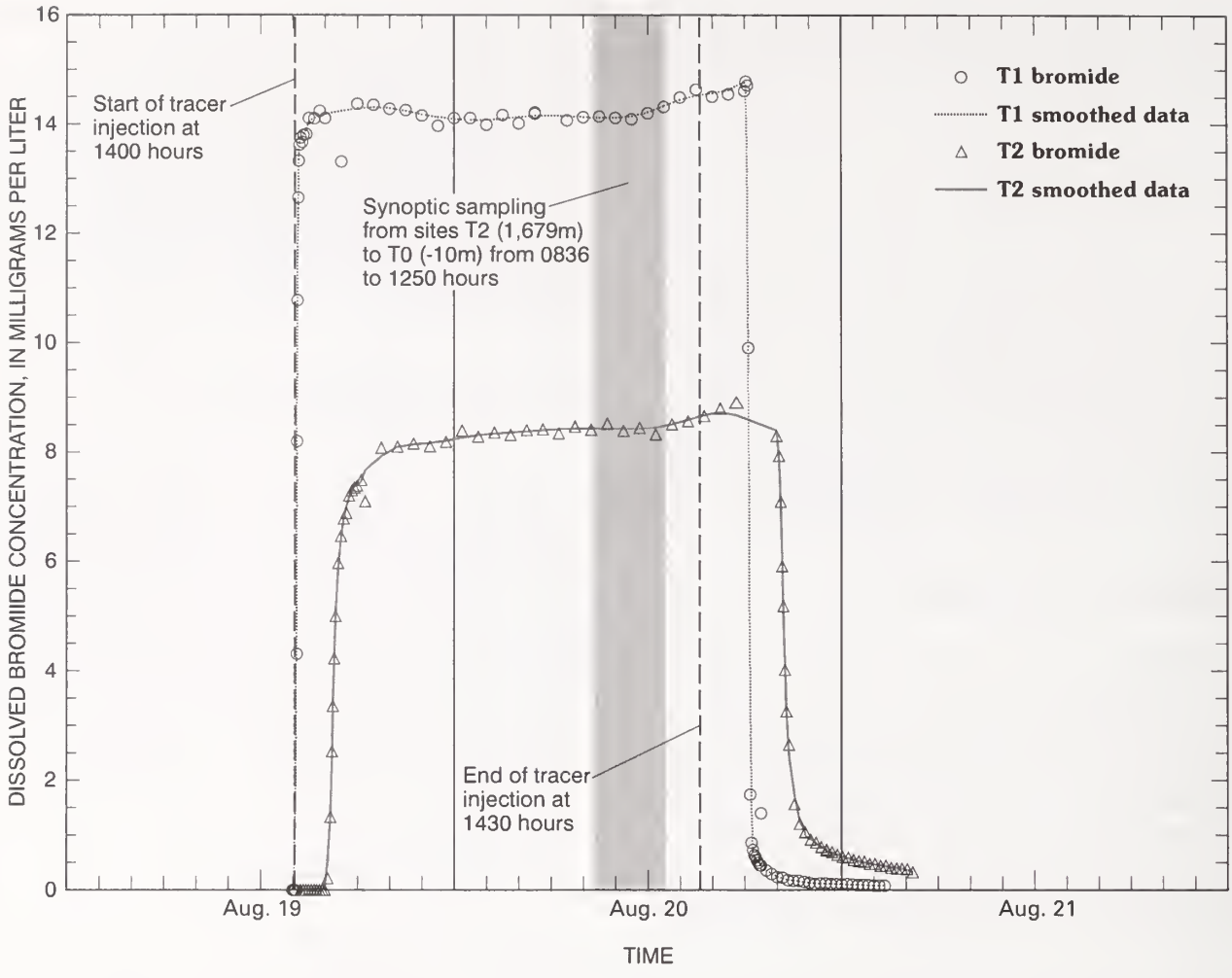


Figure 3. Variation of dissolved bromide concentration with time at transport sites T1 and T2, Soda Butte Creek, Montana, August 1999.

Discharge measurements were made at the four downstream transport sites using a standard current meter (fig. 6) as described by Rantz and others (1982a, 1982b). Current-meter discharge measurements indicated that Soda Butte Creek generally gained water along its entire reach. This flow increase results from surface inflows and ground water discharging from the near-stream valley-fill aquifer (Montana Bureau of Mines and Geology, 1999, p. 33, 38). Measured (current meter) and calculated (tracer) discharge values diverged downstream of site 1,785 m. At the YNP boundary the calculated discharge was 2,988 L/s, whereas the measured discharge was 1,076 L/s. This study was done during baseflow conditions, and the discharge in the study reach was relatively stable. Examination of the instantaneous discharge recorded at USGS gaging station 06187915 (fig. 2) revealed a slight diurnal, with a minimum discharge at midday.

Five seeps from the McLaren Mine tailings impoundment were sampled between mainstem sites 565 m and 642 m. The increase in streamflow between 565 m and 642 m was apportioned between the 5 seeps based on mass-balance calculations of specific conductance and major ions.

A discharge profile for Soda Butte Creek was constructed using the instream bromide tracer concentrations in each synoptic sample. Discharge at the first site downstream of the injection site was calculated using equation 1. The calculated discharge and instream tracer concentration at the next downstream mainstem sampling site were used to calculate the discharge at the next downstream mainstem sampling site and each subsequent sampling site downstream to site 1,785 m using equation 2 (fig. 6).

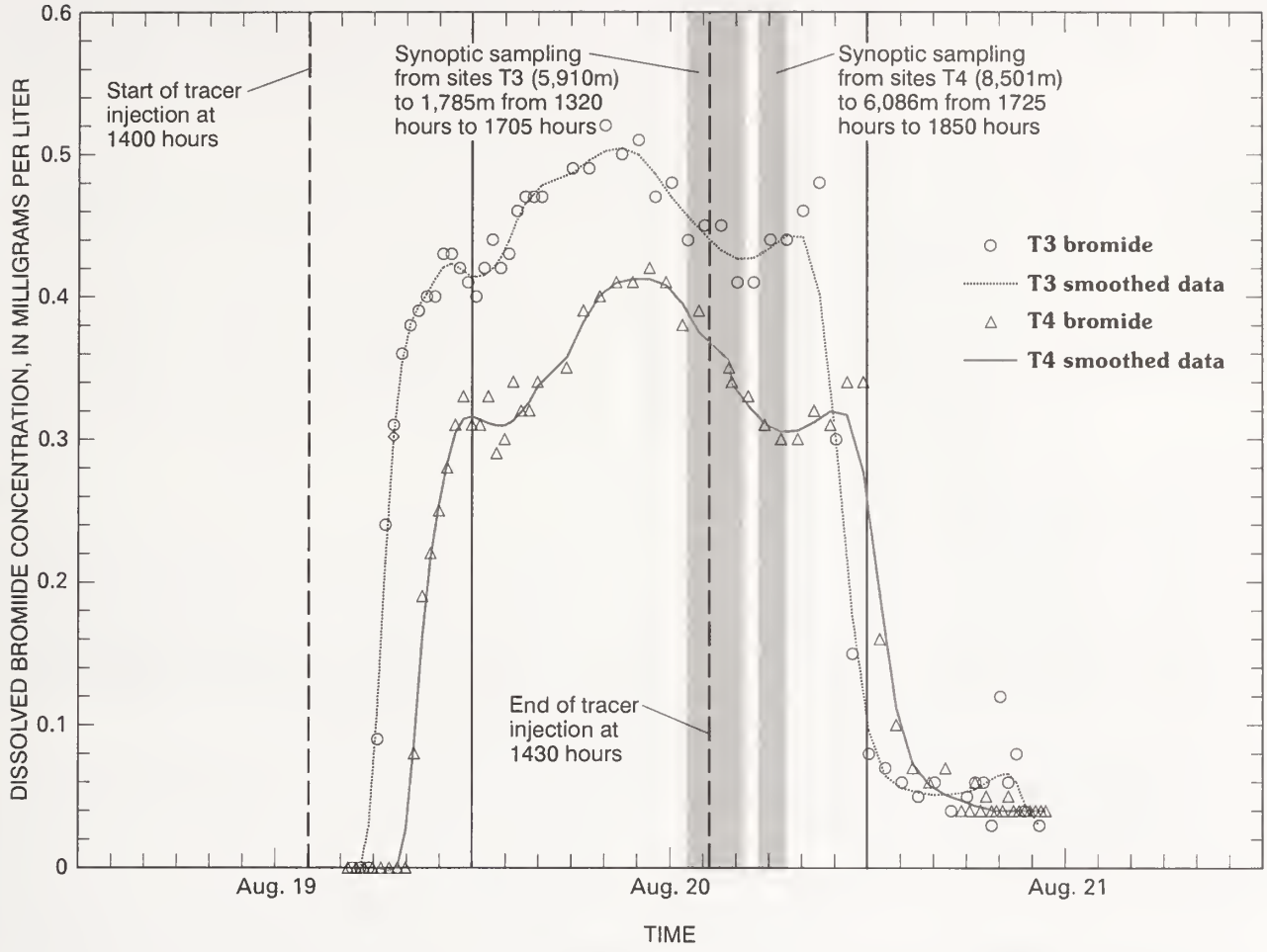


Figure 4. Variation of dissolved bromide concentration with time at transport sites T3 and T4, Soda Butte Creek, Montana and Wyoming, August 1999.

Unexpected problems with the tracer created difficulties in calculating the stream discharge downstream of site 1,785 m. The tracer was expected to reach plateau concentration at site T4 before synoptic sampling began. The tracer-calculated discharge below 1,785 m was unrealistically high, indicating that the tracer never reached plateau concentration downstream of this location. In addition, a steady rain began falling while sites 7,745 m to 6,086 m were sampled. Instantaneous discharge measured at USGS gaging station 06187915 increased nearly six percent while sites 7,745 m to 6,086 m were sampled. Tracer concentrations in samples from sites 7,745 m to 6,086 m may have been affected by dilution caused by the rainfall.

Because of the uncertainties associated with the tracer-calculated discharges downstream of site 1,785 m, the constituent loads downstream of site 1,785 m were calculated using the discharges measured with a current meter at sites T3 and T4. Discharge probably was underestimated between sites 1,785 m and T4 using the measured discharge values. Studies conducted in similar areas have shown the tracer-calculated discharge to be about 30 percent greater than the current-meter discharge (Kimball and others, 1998). Two significant visible inflows, Republic Creek (1,859 m) and Sheep Creek (3,623 m) occurred between sites T2 and T3 (fig. 6). The increase in discharge along this reach was attributed to Republic Creek and Sheep Creek. The relative streamflow contributions of Republic Creek and Sheep Creek were determined from the difference in the bromide concentrations of the sites bracketing the inflows. Between sites T3 and T4 the increase in streamflow was assumed to be contributed by the only major visible

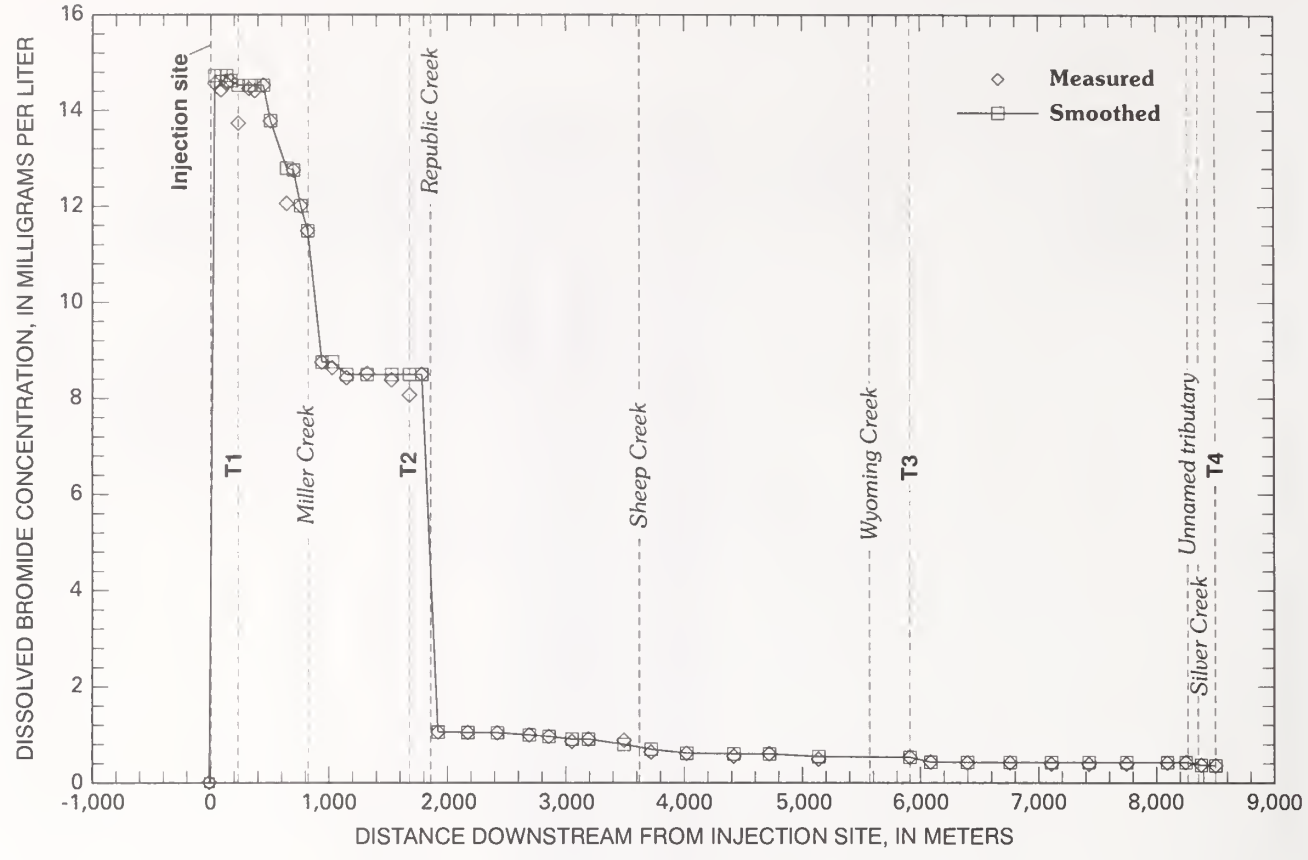


Figure 5. Variation of dissolved bromide concentration with distance, Soda Butte Creek, Montana and Wyoming, August 20, 1999.

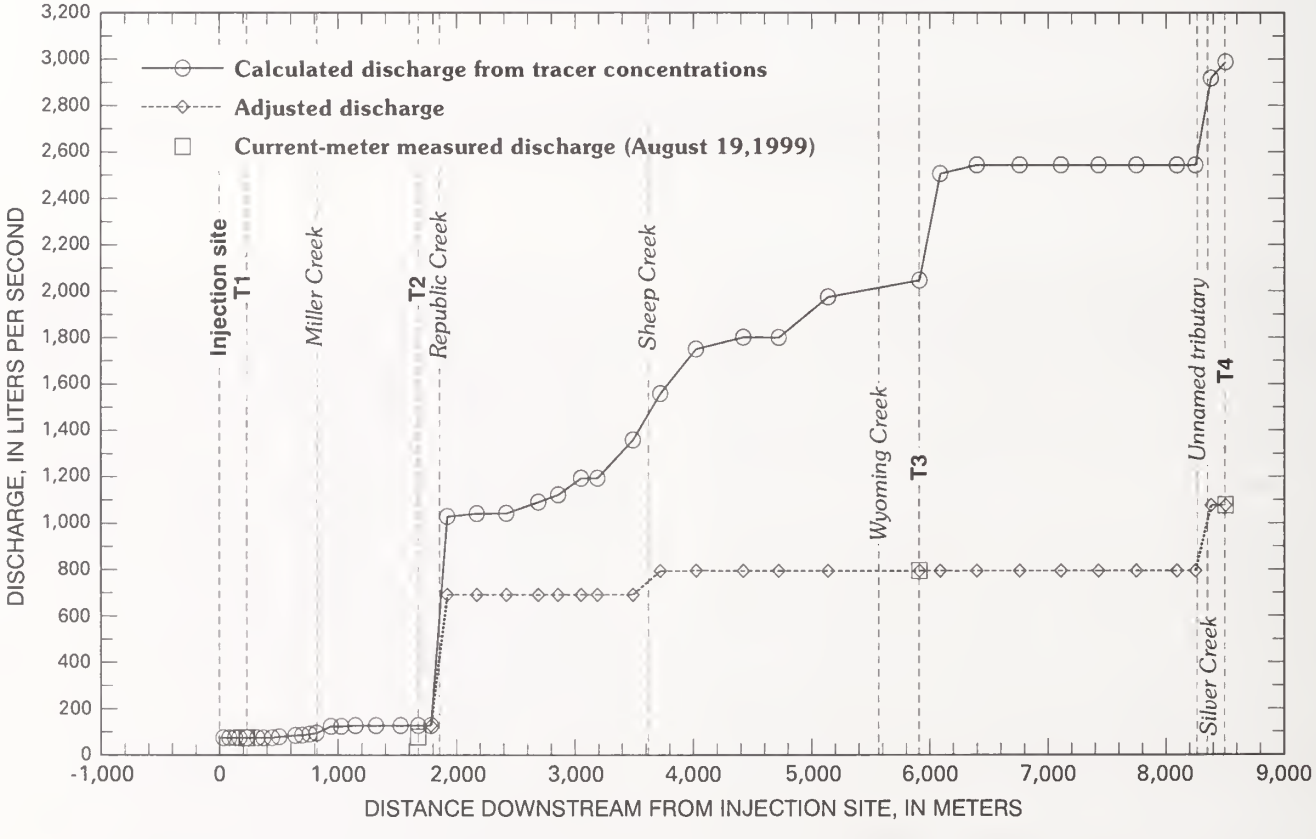


Figure 6. Discharge profile downstream from the injection site, Soda Butte Creek, Montana and Wyoming, August 20,1999.

inflow along that reach, Unnamed Tributary (8,267 m). Using the measured discharge values yielded minimum estimates of metal loading downstream of site 1,785 m.

Synoptic-Sampling Results

Results of chemical analysis of water samples collected at the synoptic-sampling sites are listed in appendixes B and C. The data are sorted by mainstem and inflow sites and are listed in downstream order.

Inflows

The quality of water in Soda Butte Creek was affected by numerous surface and subsurface inflows. pH values, specific-conductance values and sulfate concentrations are discussed in detail because they are significantly influenced by acid mine drainage.

Runkel and others (1999) described pH as "a master variable that influences the sorption of copper and other trace metals." The hydroxide precipitates of most metals are quite insoluble under natural water pH conditions. Hydroxide-ion activity has a direct relation to pH, resulting in increased solubility of hydroxide precipitates with decreasing pH (Elder, 1988, p. 11). The pH of some inflows was much lower than the pH in Soda Butte Creek. The graph of pH versus distance downstream from the injection site illustrates this point (fig. 7). From 146 m to 455 m, the mainstem pH varied between 7.6 and 8.3. These slightly alkaline inflows were located upstream of any influence from the McLaren Mine tailings. The lowest pH of any sample (4.0) was measured at the next downstream inflow (569 m). From 569 m to 643 m, acidic inflows entered the creek and the stream bottom was heavily stained with iron oxyhydroxides. All of the acidic inflows entered the creek on the left bank, indicating they were coming from the McLaren Mine tailings impoundment rather than the mill site. Downstream of 643 m, the pH remained above 7.0 in all inflows.

Mine drainage typically has high specific-conductance values. Specific-conductance values were high in comparison to the mainstem sites in the inflows from 569 m to 710 m (fig. 8). As was the case with low pH, this occurred along the section of the creek receiving inflow from the McLaren Mine tailings impoundment. Downstream of 710 m the specific-conductance values of the inflows were in closer agreement with specific-conductance values in Soda Butte Creek.

Mine drainage also has high concentrations of sulfate because of the oxidation of sulfide minerals. Sulfate concentrations were high in the inflows from 569 m to 710 m (fig. 9). As with low pH and high specific conductance, this occurred along the section of the creek receiving inflow from the McLaren Mine tailings impoundment. Concentrations of sulfate decreased downstream because of the large dilution effect from Republic Creek (1,859 m).

In general, the ground-water inflows downgradient of the McLaren Mine tailings impoundment contained higher concentrations of constituents than the surface-water inflows. This is probably attributable to the acidic, reduced conditions as well as longer contact times with the source materials. The highest concentrations of total-recoverable aluminum (122 mg/L), cadmium (0.063 mg/L), copper (6.08 mg/L), iron (418 mg/L), nickel (0.200 mg/L), lead (0.603 mg/L), and zinc (0.772 mg/L) were all detected in the sample collected at 569 m (append. C). This ground-water seep is downgradient of the McLaren Mine tailings impoundment.

No inflows originated from the McLaren mill site. However, this study was conducted during the low-flow season. Rill erosion was evident at the mill site immediately upgradient of Soda Butte Creek. During the spring snowmelt season, as well as during significant summer rainstorms, the McLaren mill site probably contributes to the metal loading of Soda Butte Creek.

Mainstem

Concentrations of the various constituents present in mine drainage can vary widely in time and space. The mainstem constituent concentration generally will reach some value that is between the maximum and minimum concentrations of inflows (Bencala and McKnight, 1987, p. 257). Normalization of concentrations relative to the sampled range of inflow concentrations renders the various constituents more comparable (Kimball and others, 1999). Instream concentrations are normalized by the equation (Bencala and McKnight, 1987, p. 258):

$$C_{NORM} = (C_S - C^I_{MIN}) / (C^I_{MAX} - C^I_{MIN}) \qquad (3)$$

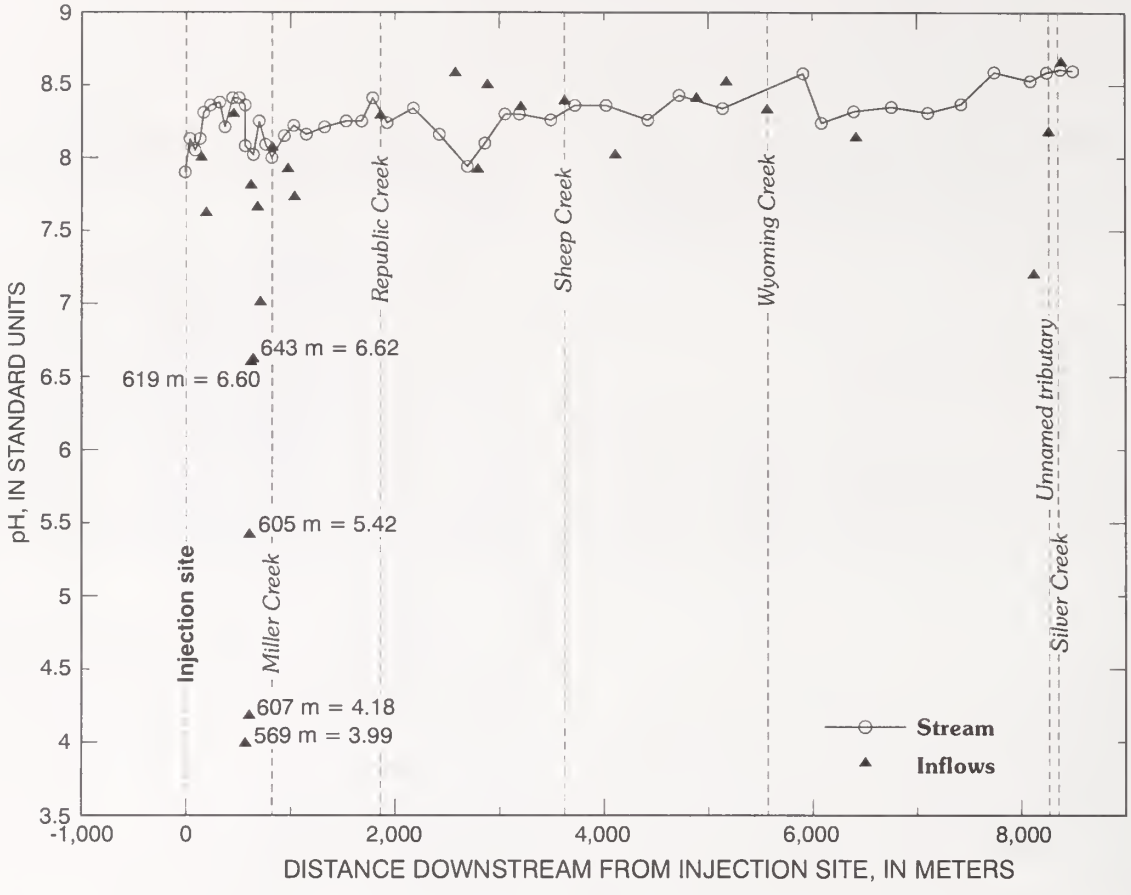


Figure 7. Variation of stream and inflow pH with distance from the injection site, Soda Butte Creek, Montana and Wyoming, August 20, 1999.

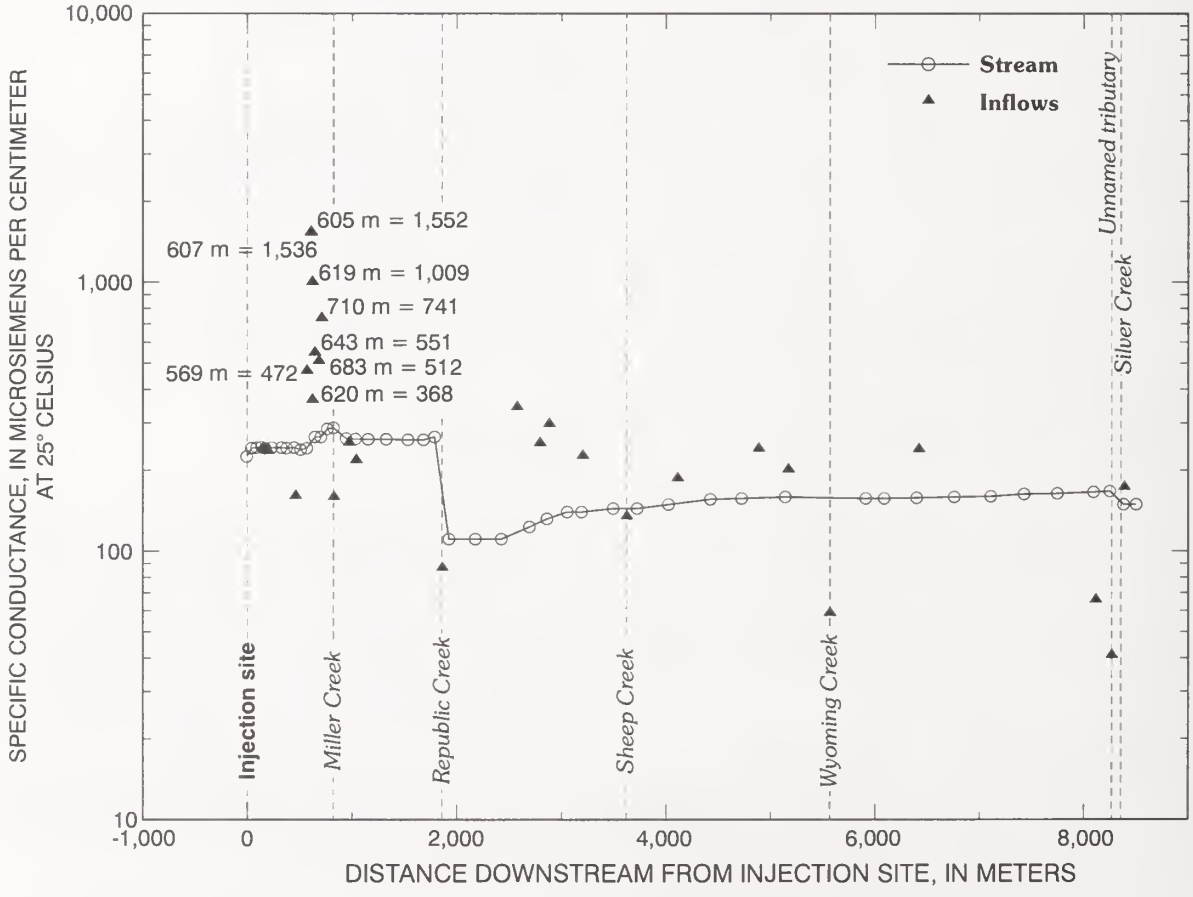


Figure 8. Variation of stream and inflow specific conductance with distance from the injection site, Soda Butte Creek, Montana and Wyoming, August 20, 1999.

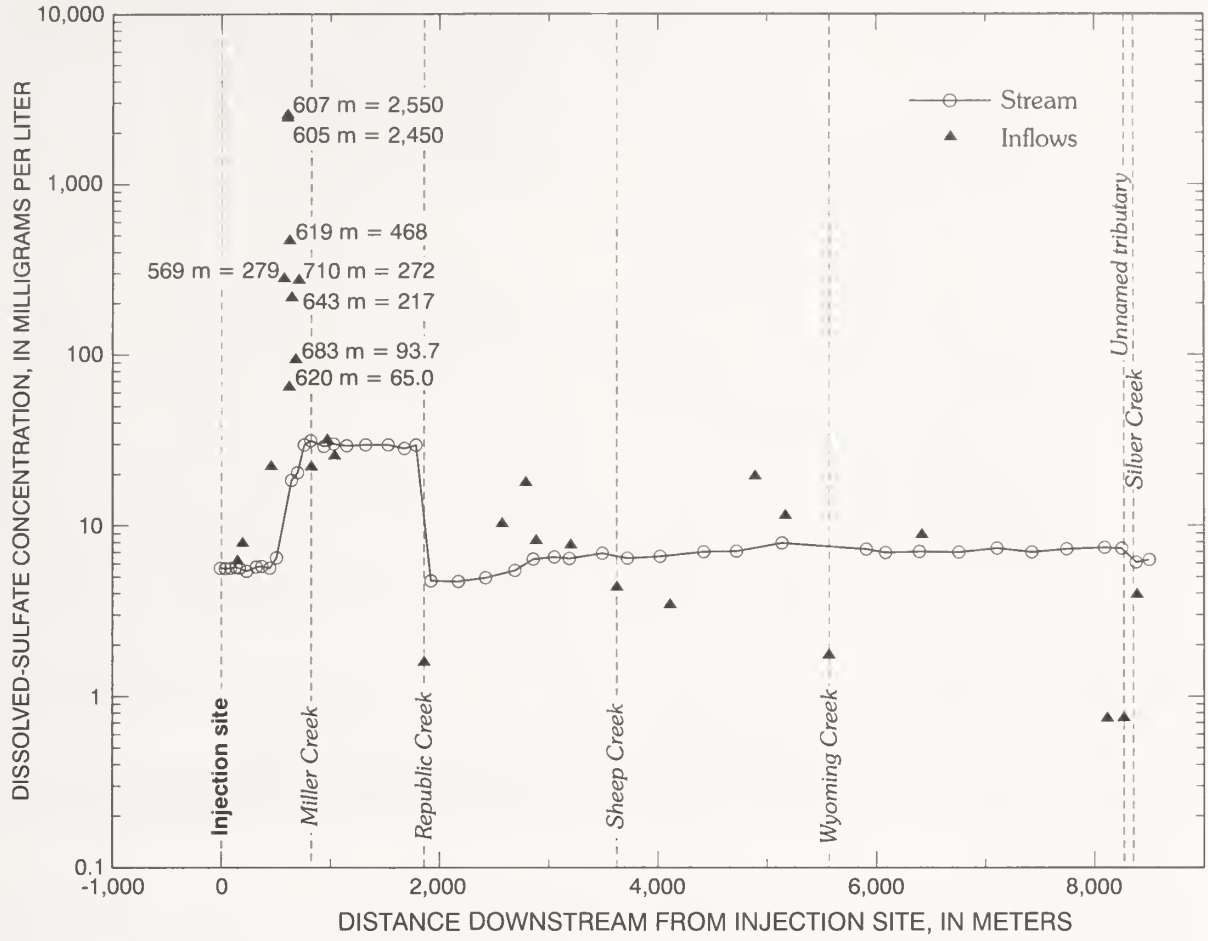


Figure 9. Variation of stream and inflow dissolved sulfate concentration with distance from the injection site, Soda Butte Creek, Montana and Wyoming, August 20, 1999.

Where C_{NORM} is the normalized concentration relative to the range of inflow concentrations,

C_S is the instream concentration at a given distance downstream from the injection,

C^I_{MIN} is the minimum inflow concentration for the constituent, and

C^I_{MAX} is the maximum inflow concentration for the constituent.

C_{NORM} will be 1 if the instream concentration is equal to the maximum inflow concentration and will be 0 if the instream concentration is equal to the minimum inflow concentration.

Weathering of the Meagher and Pilgrim Limestones in the upper Soda Butte Creek basin produced most of the calcium and magnesium ions detected in the stream above Republic Creek. Quartz "Eye" Rhyodacite Porphyry and Quartz Dolerite are the principal sources of the potassium and strontium (Elliott, 1979). Weathering is the result of natural processes but can be greatly accelerated by mining activities. Normalized concentrations of all four total-recoverable constituents were highest upstream of Republic Creek and decreased because of the large dilution effect from Republic Creek (fig. 10).

Aluminum and silica detected in the water result from both mining activities and natural weathering of feldspars and other aluminosilicate minerals in the watershed. Inflow contributed by Republic Creek increased normalized concentrations of total-recoverable aluminum and silica (fig. 11). Bedrock in the Republic Creek basin consists largely of the Lamar River and Wapiti Formations, which are andesitic volcanic conglomerates containing clasts of the aluminosilicate minerals pyroxene and hornblende (Pierce and others, 1973).

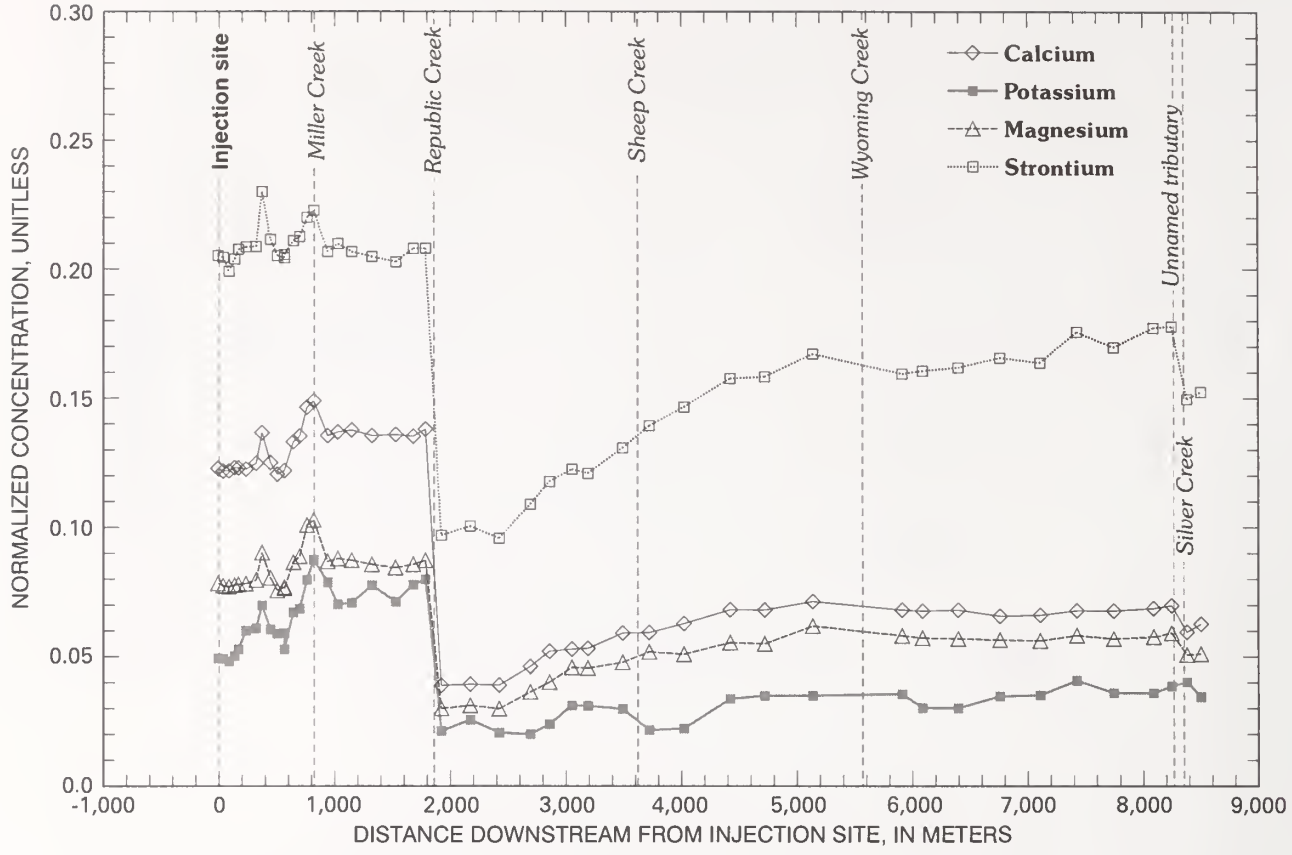


Figure 10. Variation of normalized total-recoverable concentrations of calcium, potassium, magnesium, and strontium with distance from the injection site, Soda Butte Creek, Montana and Wyoming, August 20, 1999.

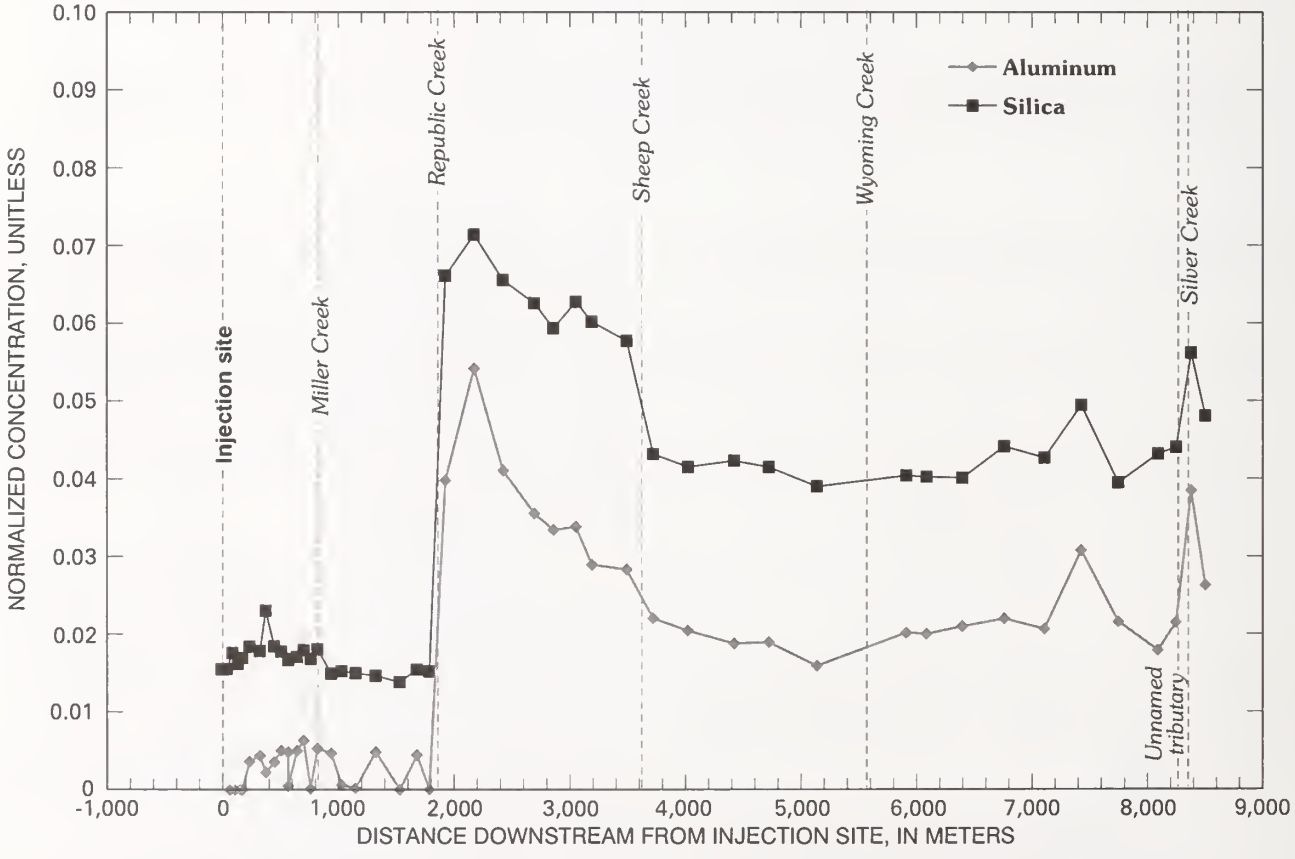


Figure 11. Variation of normalized total-recoverable concentrations of aluminum and silica with distance from the injection site, Soda Butte Creek, Montana and Wyoming, August 20, 1999.

Some of the inflow samples downgradient of the McLaren Mine tailings impoundment contained iron concentrations two orders of magnitude higher than any of the stream samples. In this case, a plot of normalized iron would not be instructive, so the actual dissolved and total-recoverable concentrations were plotted instead (fig. 12).

Iron concentrations were very low at all sites upgradient of the McLaren Mine tailings impoundment. Total-recoverable concentrations increased sharply where the acidic ground water from the tailings entered the creek, decreased rapidly, and then varied downstream in response to other inflows. The highest total-recoverable concentration of iron in the synoptic water samples from Soda Butte Creek was 1.30 mg/L at 820 m (append. C). The streambed of Soda Butte Creek was heavily stained by iron hydroxide deposits along this segment of the creek downgradient of the McLaren Mine tailings impoundment.

Results of chemical analysis of water samples collected for the NAWQA program at USGS gaging station 06187915 (Soda Butte Creek at YNP boundary, near Silver Gate, Montana; fig. 2) for water year 1999 are listed in appendix D. The location of the gage corresponds to the downstream end of the study reach (8,501 m) and transport site T4. Metal concentrations in the NAWQA samples were similar to the results obtained from the tracer-synoptic samples. The NAWQA samples were analyzed using inductively coupled plasma-mass spectrometry (ICP-MS). Discharge and constituent concentrations vary considerably throughout the water year. As a result, the metal loads also vary considerably with time. The water sample collected on June 22, at peak snowmelt runoff, contained the highest total-recoverable concentrations of aluminum (4.64 mg/L), chromium (0.0048 mg/L), copper (0.022 mg/L), iron (6.26 mg/L), lead (0.013 mg/L), manganese (0.210 mg/L), and nickel (0.013 mg/L) of any the samples collected during the 1999 water year (append. D). Because this sample was collected during the time of greatest discharge, the metal loads were much higher than they were for any other sample collected in 1999.

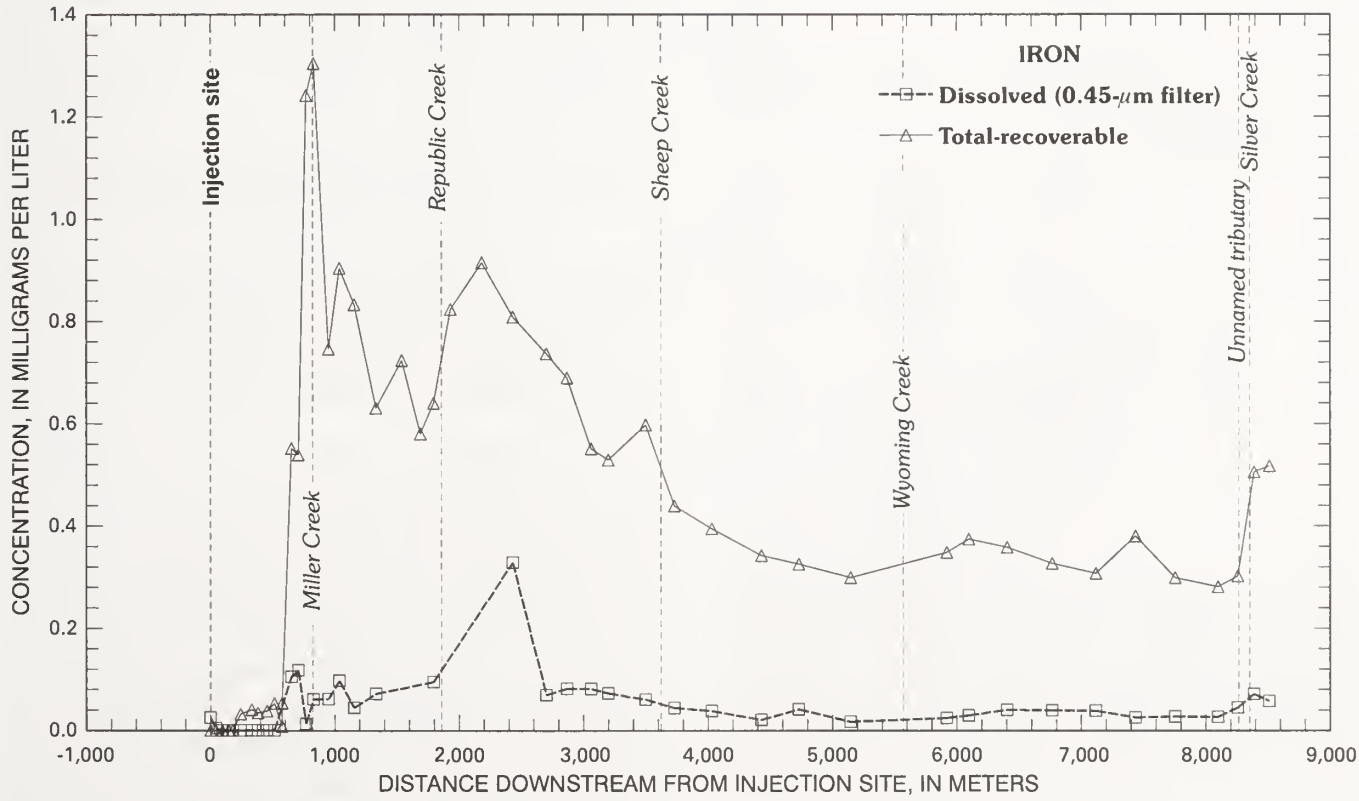


Figure 12. Variation of concentrations of dissolved and total-recoverable iron with distance from the injection site, Soda Butte Creek, Montana and Wyoming, August 20, 1999.

Quantification of Loads

Data from the tracer-injection and synoptic-sampling study were used to calculate the instantaneous load, or mass, of select constituents carried by Soda Butte Creek at the synoptic-sampling sites. The load for any stream site is the product of stream discharge (Q) and concentration (C). For example, the load at site A would be $Q_A C_A$. Loads from sites -10 m to 1,785 m were calculated using stream discharge determined by tracer dilution. Loads downstream of site 1,785 m were calculated using stream discharge measured by current meter at sites T3 and T4. The loading of constituents at different points in the stream was compared to isolate areas of surface- or groundwater inflow that may be contributing constituents to the stream or diluting them.

Solute transport in streams is governed by a suite of hydrologic and chemical processes. These processes can result in a change in the metal load transported by a stream. Hydrologic transport processes include advection, dispersion, lateral inflow, and transient storage. Chemical processes include formation of precipitates, dissolution, sorption, complexation, and reduction-oxidation reactions (Runkel and others, 1999).

The instream change in load between the upstream site A and the downstream site B, $\hat{}M_S$, is calculated from the equation:

$$\hat{}M_S = (Q_B C_B - Q_A C_A) \text{ (Kimball and others, 1999, p. 5)} \quad (4)$$

where $\hat{}M_S$ is the net change in stream load between sites A and B,
Q_B is the discharge at site B,
C_B is the constituent concentration at site B,
Q_A is the discharge at site A, and
C_A is the constituent concentration at site A.

There are two ways to account for $\hat{}M_S$ between stream sites, depending on whether the change in load is caused by a visible sampled inflow or a subsurface inflow. If a sampled inflow concentration represents the concentration of all the water entering between sites A and B, then the change in load also can be calculated from:

$$\hat{}M_I = C_I (Q_B - Q_A) \text{ (Kimball and others, 1999, p. 5)} \quad (5)$$

Where $\hat{}M_I$ is the net change in stream load between sites A and B,
C_I is the inflow concentration,
Q_B is the discharge at site B, and
Q_A is the discharge at site A.

$\hat{}M_I$ is called the "sampled inflow load" for this study.

If no visible inflow was present between sites A and B, but a subsurface inflow caused an increase in load, then the average inflow concentration for the segment can be calculated by rearranging equation 5 to solve for C_I to represent the subsurface inflow concentration. If the constituent was removed by chemical reaction between sites A and B, however, the calculated value of C_I will be an underestimate of the average inflow concentration (Kimball and others, 1999). In this case it is not possible to determine the relative contributions of the ground water and surface water to the constituent loading.

For each stream segment, ^Ms represents the net change in load. This may represent an overall loss in mass. The possibilities are summarized below:

Condition	Probable explanation
$\hat{}M_S = \hat{}M_I$	The value of C_I represents the concentration of all the water entering the stream.
$\hat{}M_S > \hat{}M_I$	Subsurface inflow has a concentration greater than C_I.
$\hat{}M_S < \hat{}M_I$	Could indicate two conditions: (1) load is lost through chemical reaction within the subreach or (2) subsurface inflow has a concentration less than C_I.
$\hat{}M_S < 0$	There is a net loss of load through chemical reaction within the stream subreach.

(From Kimball and others, 1999, p. 6)

Three profiles are shown on the plots of loads versus distance downstream from injection site (figs. 13-21). The sampled instream load is calculated by multiplying the constituent concentration in the synoptic water sample by the stream discharge at that site. Instream loads change downstream because of gains from the surface and subsurface inflows and losses from chemical or physical processes. The total-recoverable load minus the dissolved load equals the particulate load—predominantly colloids. Summing all increases in instream load values and disregarding any loss in mass from chemical or physical processes yields cumulative instream load. The cumulative

inflow load is the sum of all the inflow loads. For concentrations reported as less than the minimum reporting level (MRL) the loads were calculated using a concentration equal to one-half the MRL.

Major Ions

The shape of the load profiles of the major ions indicates the locations of the major sources of those ions. Calcium detected in the stream originated mainly from weathering of limestone formations in the upper reaches of the basin. The largest contributions to the cumulative inflow load of dissolved calcium were by inflows between 505 m and 940 m (16 percent), between 1,785 m and 2,422 m (40 percent), and between 3,490 m and 3,720 m (16 percent) (fig. 13). The sampled instream load profile of dissolved calcium is similar to the cumulative instream load profile, indicating that little calcium was removed by chemical or physical processes in the stream. The cumulative inflow load was 51 percent of the cumulative instream load, indicating that the visible sampled inflows likely had lower calcium concentrations than the subsurface inflows.

The load profiles of dissolved silica are dominated by the contributions of Republic Creek (1,859 m). The cumulative inflow load of dissolved silica (fig. 14) was attributable mainly to two areas: inflows between 1,785 m and 2,422 m (53 percent) and between 8,247 m and 8,379 m (34 percent). The cumulative instream load was contributed mainly by inflows between 1,785 m and 2,422 m (67 percent) and between 8,247 m and 8,379 m (24 percent). The sampled instream load profile and cumulative instream load profile are similar, indicating that little silica was removed from the water column by chemical or physical processes.

The load profiles of dissolved sulfate reflect the effects of the ground-water seeps from the McLaren Mine tailings impoundment. Most of the cumulative inflow load of dissolved sulfate was contributed by the inflows between 505 m and 940 m (72 percent) (fig. 15). The cumulative instream load was contributed mainly by inflows between 505 m and 940 m (42 percent) and between 8,247 m and 8,379 m (13 percent). The sampled instream load and cumulative instream load profiles are similar. The difference between the smaller cumulative inflow load and the larger cumulative instream load indicates that the visible sampled inflows had lower sulfate concentrations than the subsurface inflows.

Metals

Metals bound to colloidal particles make up most of the difference between the total-recoverable and dissolved concentrations. Iron colloids are of particular interest because they have been shown to play a key role in metals transport in other Rocky Mountain streams receiving acid mine drainage (Kimball and others, 1995). Iron colloids can precipitate on the streambed and adversely affect the physical habitat of benthic aquatic organisms. Trace metals tend to sorb to iron colloids. A large percentage of the metal load in Soda Butte Creek was transported in the colloidal phase.

The load profiles of metals were more variable than those of the major ions because of physical and chemical processes in the mainstem. Iron is discussed first because of its importance in regulating the behavior of the other metals.

Accurate load calculations for iron were difficult to derive because of the highly reactive nature of this metal. Dissolved iron loads were small because most of the iron rapidly precipitated out of the neutral-pH waters of Soda Butte Creek as colloidal ferric oxide. Cumulative inflow load was attributable almost entirely to three areas: between 505 m and 760 m (48 percent), between 1,785m and 2,422m (18 percent), and between 8,247 m and 8,379 m (32 percent) (fig. 16). Most of the cumulative instream load (66 percent) was contributed by inflows between 1,785 m and 2,422 m. The large disparity between the total cumulative instream load (326 mg/s) and the sampled instream load (68.9 mg/s) at T4 is indicative of iron removal from the stream by chemical or physical processes.

The cumulative inflow load of total-recoverable iron (fig. 17) was attributable almost entirely to three areas: between 565 m and 760 m (26 percent), between 1,785m and 1,922m (38 percent), and between 8,247 m and 8,379 m (34 percent). Significant contributions to the cumulative instream load came from inflows between 1,785 m and 1,922 m (52 percent) and subsurface inflows between 8,247 m and 8,379 m (31 percent). The sampled instream load and cumulative instream load diverge downstream of 2,172 m, indicating removal of iron by chemical or physical processes.

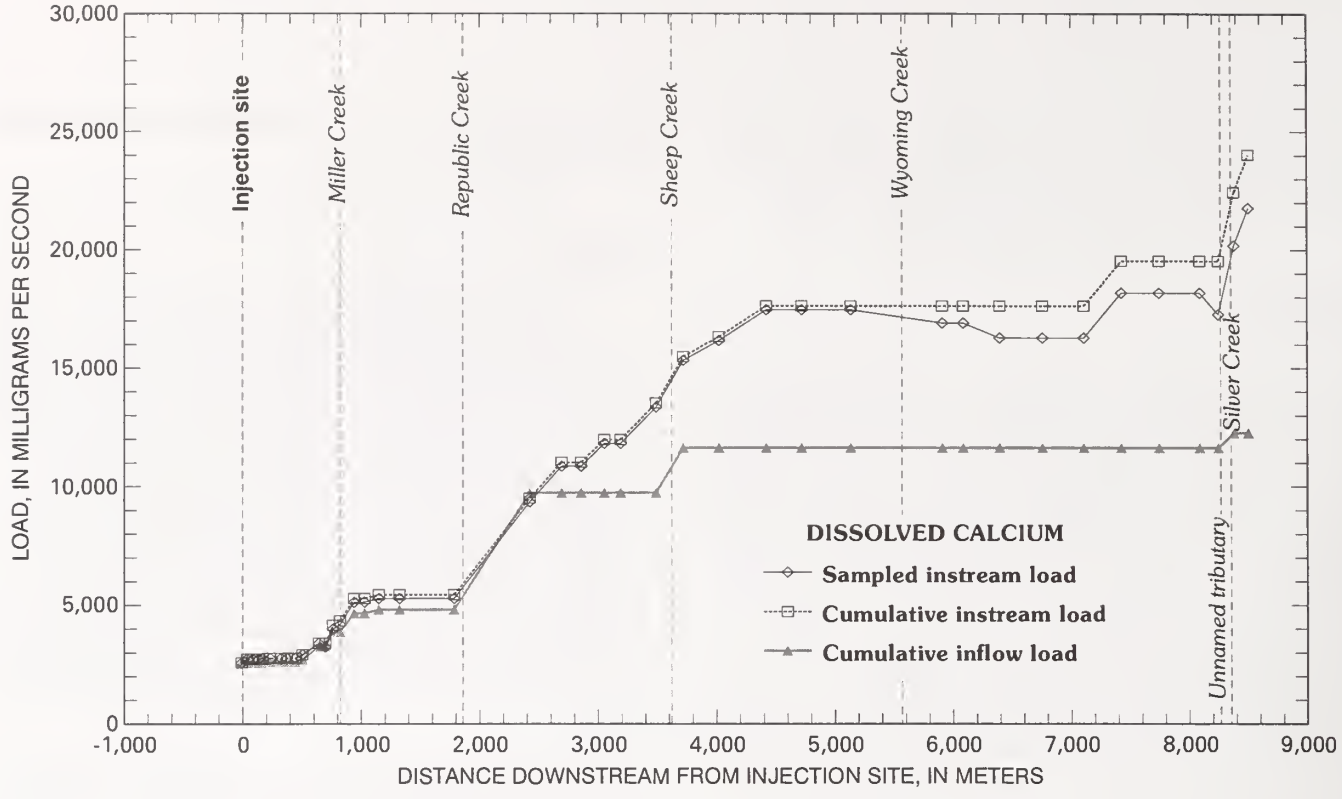


Figure 13. Sampled instream load, cumulative instream load, and cumulative inflow load of dissolved calcium, Soda Butte Creek, Montana and Wyoming, August 20, 1999.

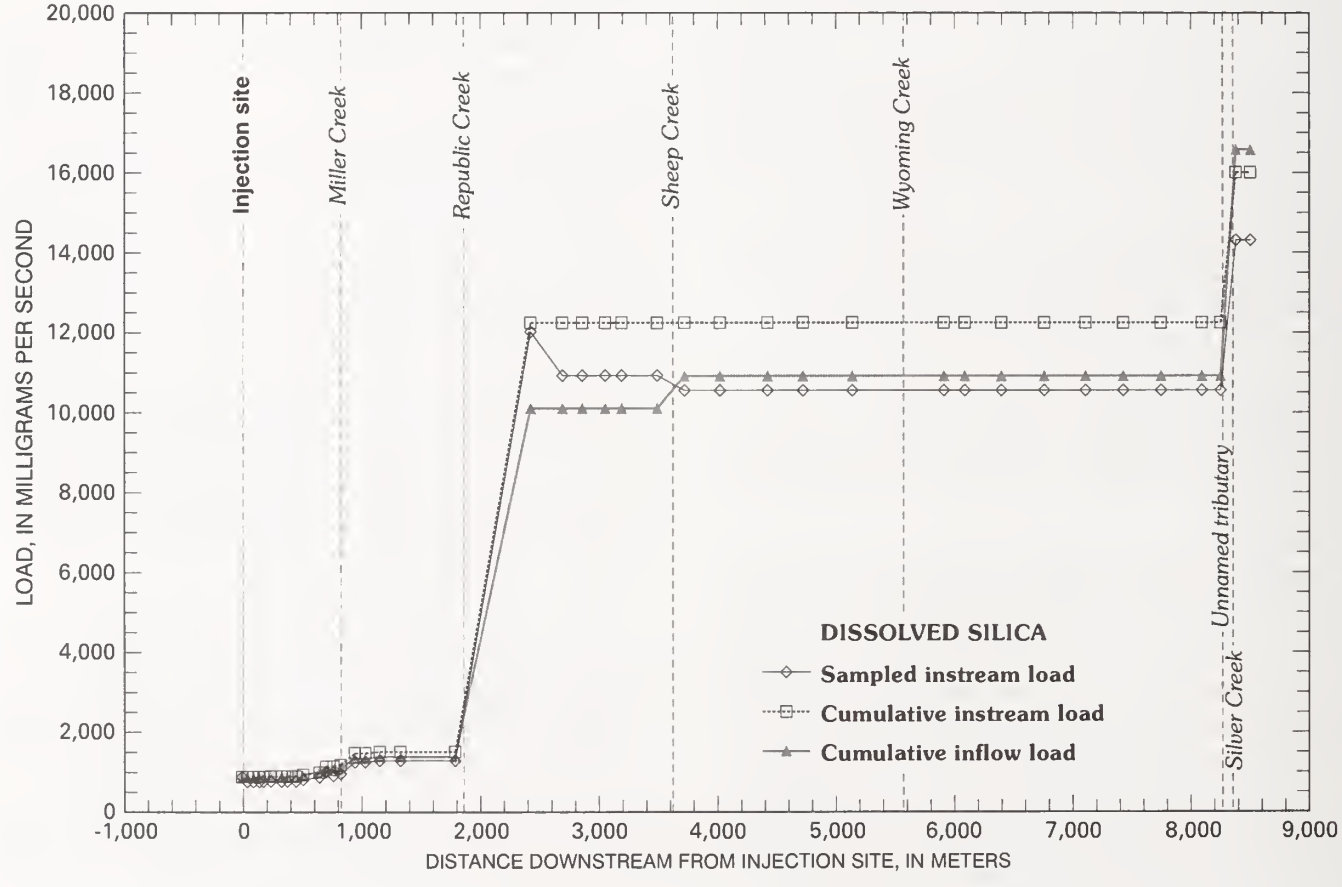


Figure 14. Sampled instream load, cumulative instream load, and cumulative inflow load of dissolved silica, Soda Butte Creek, Montana and Wyoming, August 20, 1999.

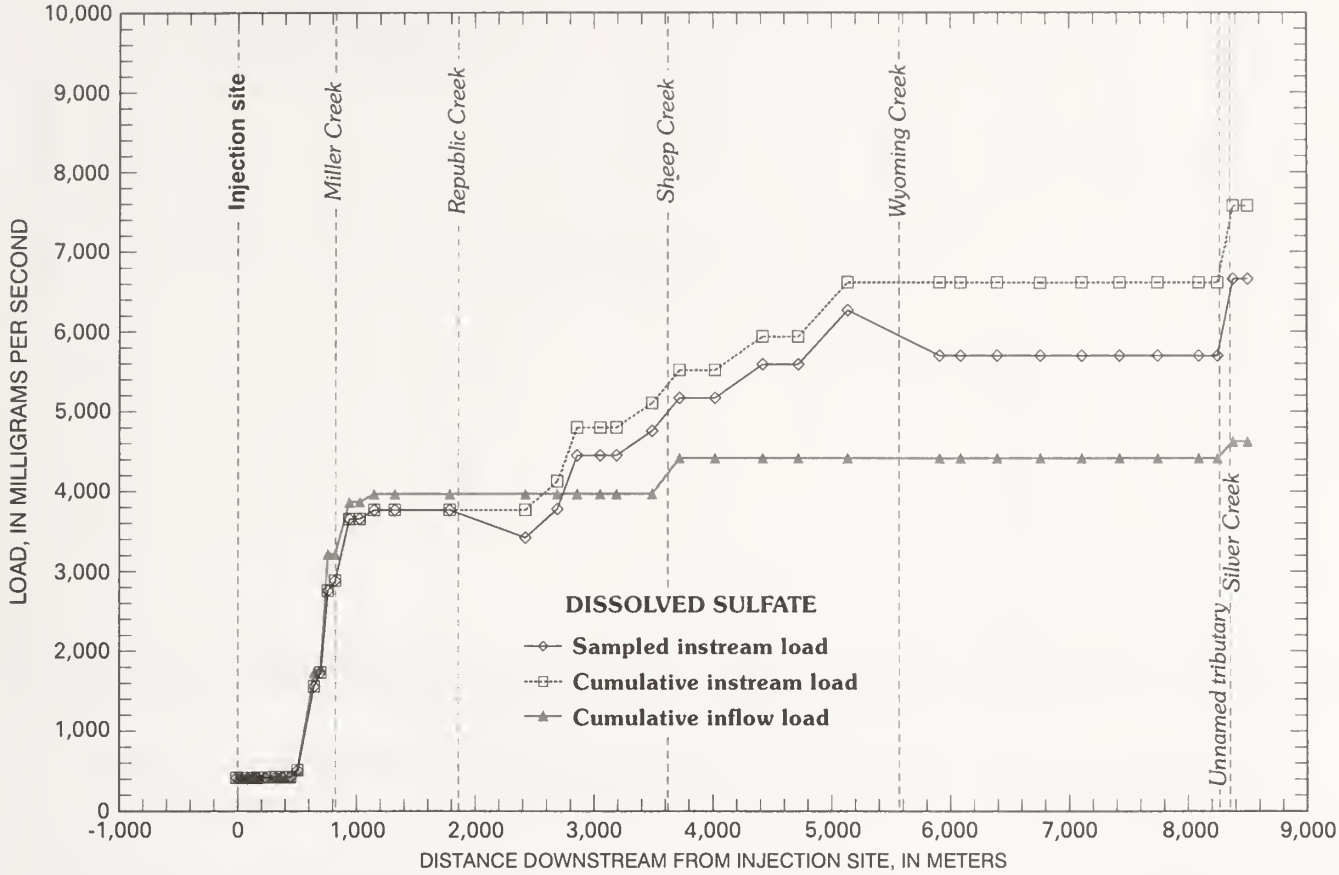


Figure 15. Sampled instream load, cumulative instream load, and cumulative inflow load of dissolved sulfate, Soda Butte Creek, Montana and Wyoming, August 20, 1999.

Most of the cumulative inflow load of dissolved aluminum was contributed by the inflows between 1,785 m and 2,422 m (44 percent) and between 8,247 m and 8,379 m (50 percent) (fig. 18). The cumulative instream load was contributed mainly by inflows between 1,785m and 2,422 m (53 percent) and between 8,090 m and 8,379 m (23 percent). The cumulative instream load profile and sampled instream load profile diverge downstream of 2,422 m, indicating removal of aluminum by chemical or physical processes in that segment of the creek.

The total-recoverable aluminum load profiles (fig. 19) were very similar to those of total-recoverable iron (fig.17). The cumulative inflow load consisted mainly of the contributions from inflows between 1,785m and 1,922m (47 percent), and between 8,247 m and 8,379 m (45 percent). Significant contributions to the cumulative instream load came from inflows between 1,785 m and 2,172 m (52 percent), and between 8,247 m and 8,379 m (35 percent). The sampled instream load profile and cumulative instream load profile diverge downstream of 2,172 m, indicating removal of aluminum by chemical or physical processes in that segment of the creek.

Manganese concentrations were relatively low. Instream load profiles of elements detected at low concentrations tend to follow the shape of the discharge profile. The cumulative inflow load of dissolved manganese (fig. 20) consisted mainly of the contributions from the inflows between 505 m and 760 m (82 percent). The cumulative instream load was contributed mainly by inflows between 1,785 m and 2,422 m (52 percent), and between 8,247 m and 8,379 m (26 percent). The sampled instream load profile and cumulative instream load profile are identical, indicating no loss of dissolved manganese from the water column.

The cumulative inflow load of total-recoverable manganese consisted mainly of the contributions from inflows between 565 m and 760 m (80 percent) and between 1,785 m and 1,922 m (9 percent) (fig. 21). The

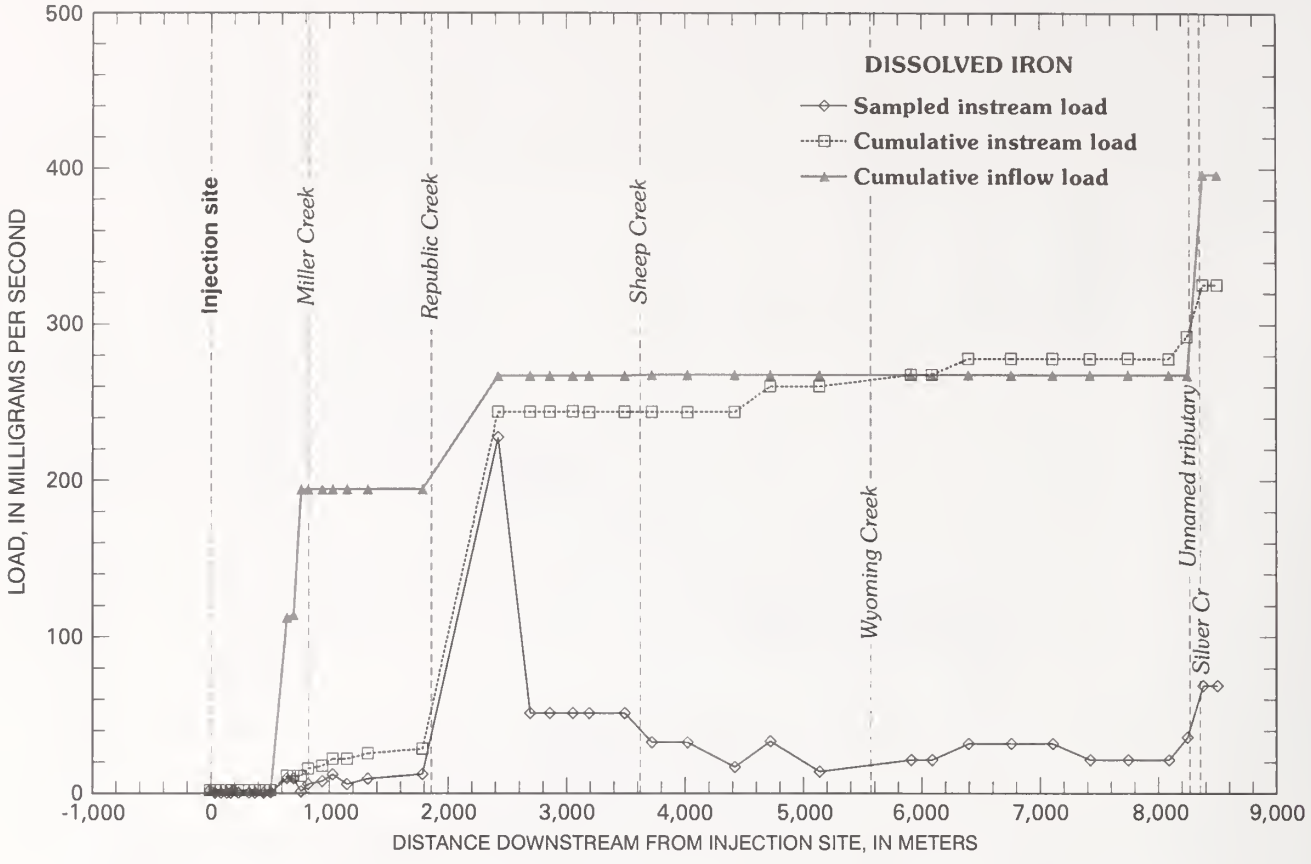


Figure 16. Sampled instream load, cumulative instream load, and cumulative inflow load of dissolved iron, Soda Butte Creek, Montana and Wyoming, August 20, 1999.

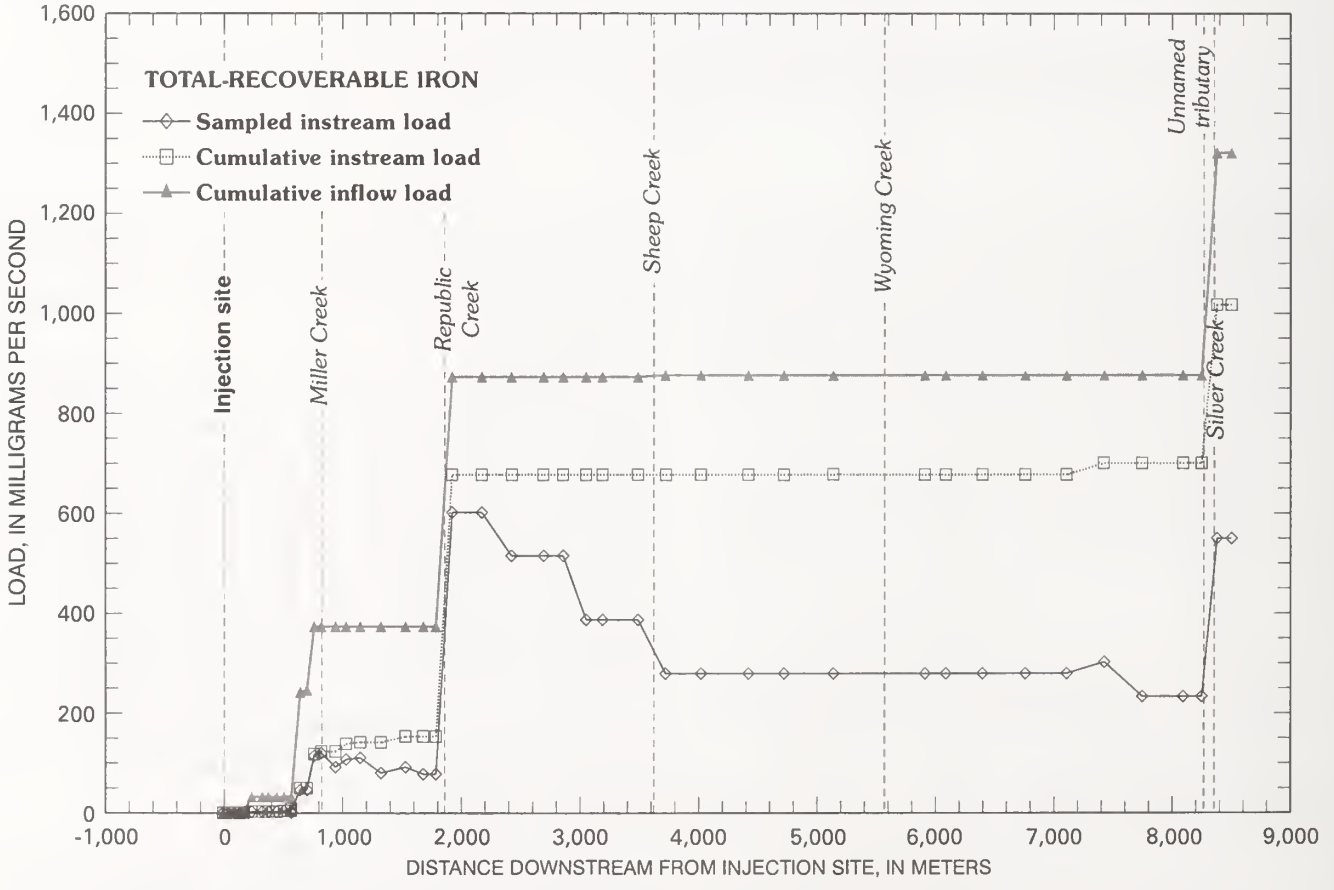


Figure 17. Sampled instream load, cumulative instream load, and cumulative inflow load of total-recoverable iron, Soda Butte Creek, Montana and Wyoming, August 20, 1999.

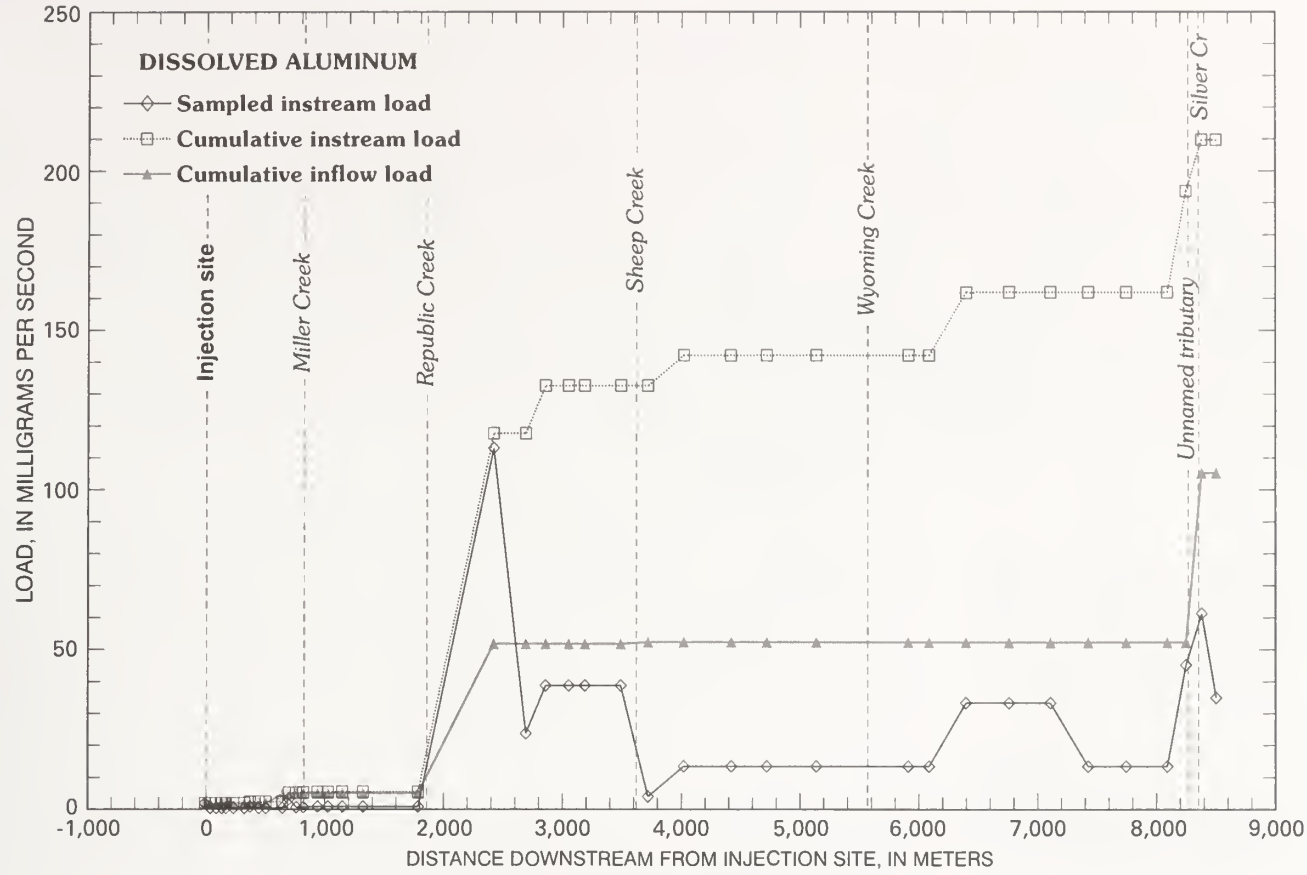


Figure 18. Sampled instream load, cumulative instream load, and cumulative inflow load of dissolved aluminum, Soda Butte Creek, Montana and Wyoming, August 20, 1999.

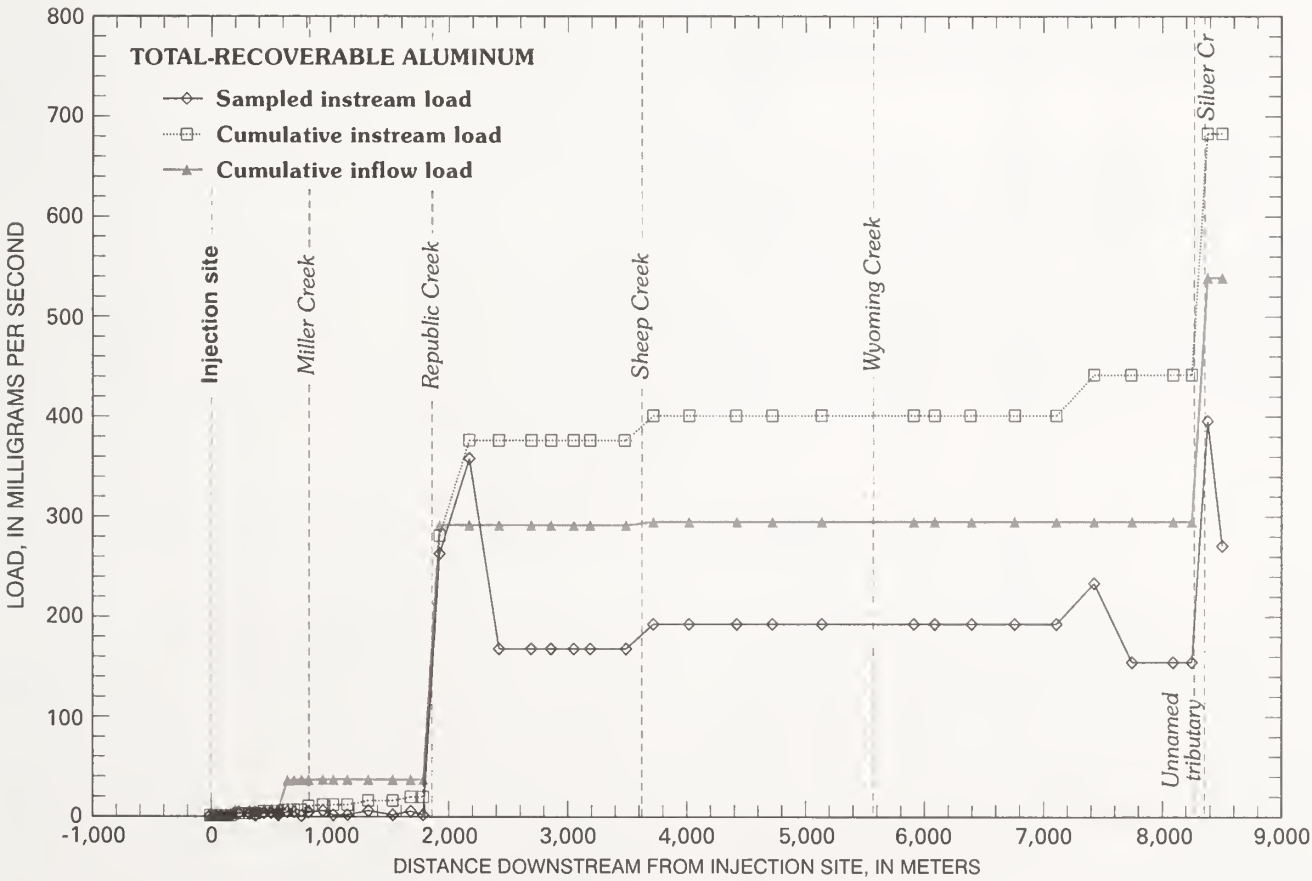


Figure 19. Sampled instream load, cumulative instream load, and cumulative inflow load of total-recoverable aluminum, Soda Butte Creek, Montana and Wyoming, August 20, 1999.

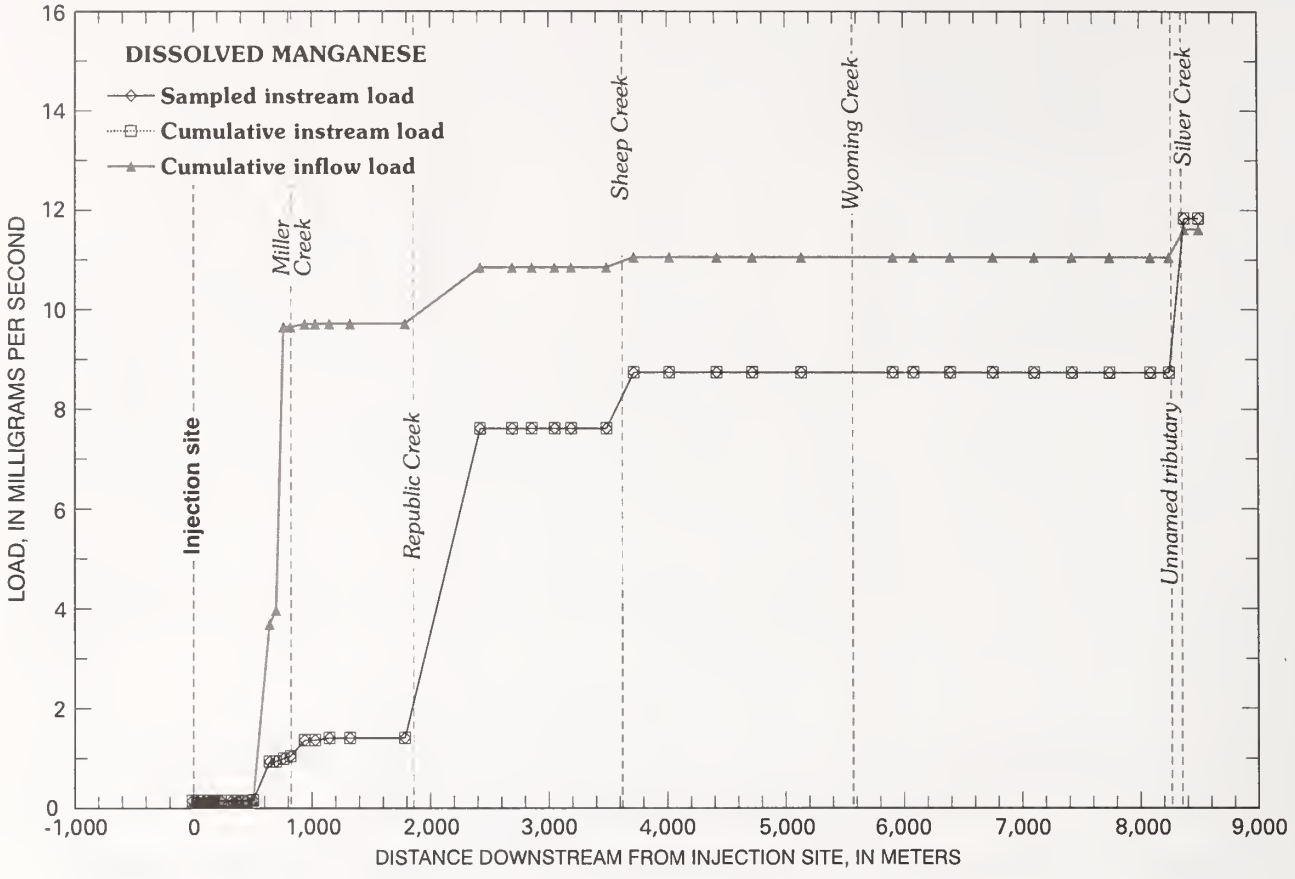


Figure 20. Sampled instream load, cumulative instream load, and cumulative inflow load of dissolved manganese, Soda Butte Creek, Montana and Wyoming, August 20, 1999.

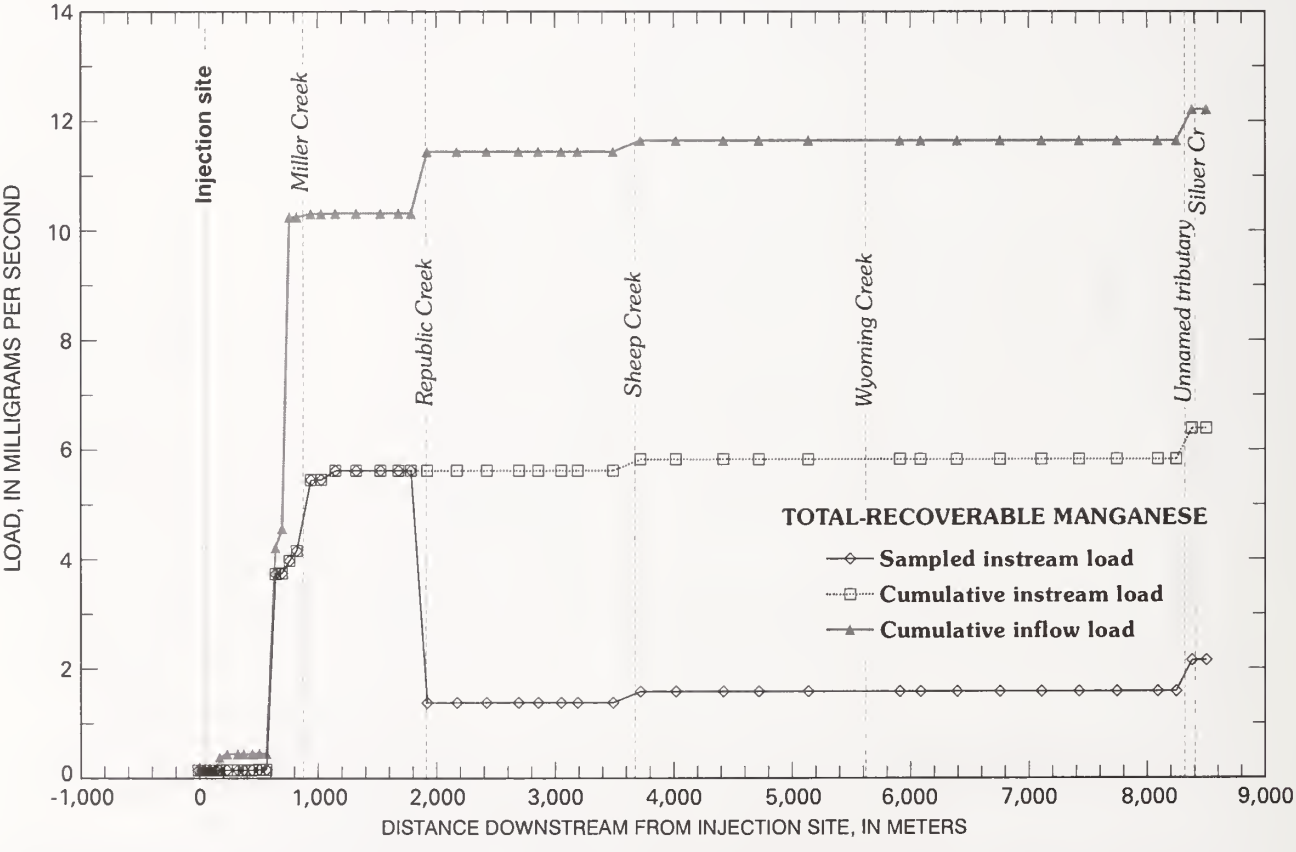


Figure 21. Sampled instream load, cumulative instream load, and cumulative inflow load of total-recoverable manganese, Soda Butte Creek, Montana and Wyoming, August 20, 1999.

cumulative instream load was contributed mainly by inflows between 565 m and 940 m (83 percent). The sampled instream load profile and cumulative instream load profile are very similar except for the stream segment from 1,785 m to 1,922 m. Along this reach, the sampled instream load dropped from 5.6 mg/s to 1.4 mg/s because of chemical or physical processes occurring in the stream.

Loads were not calculated for cadmium, copper, lead, and zinc even though minimum reporting levels for these metals approached or exceeded water-quality standards for the protection of aquatic life. The highest total-recoverable concentrations of cadmium (0.063 mg/L), copper (6.08 mg/L), lead (0.603 mg/L) and zinc (0.772 mg/L) were detected in the synoptic sample collected from site 569 m (a seep from the McLaren Mine tailings impoundment) (append. C). However, cadmium, copper, and lead were not detected in any of the mainstem synoptic samples, while the highest total-recoverable concentration of zinc in the mainstem of Soda Butte Creek was 0.044 mg/L at site 2,172 m. The lack of detection of these metals in the downstream mainstem synoptic samples, probably because of sorption (coprecipitation and adsorption) to metal colloids in the stream, prevented meaningful load calculations of these constituents.

These results agree with those of previous studies conducted in the area. Researchers analyzing water-column samples have detected very low concentrations of these elements (Miller and others, 1997). Other researchers analyzing the aquatic biota have attributed a decline in stream health along this segment of the creek to elevated trace-element concentrations, particularly copper (Forstner and Wittman, 1983; Nimmo and Willox, 1996).

Iron-rich colloids that settle to the streambed or are trapped by algae on streambed cobbles are flushed by snowmelt runoff the following year (Kimball and others, 1999). The water sample collected at the USGS gaging station at the YNP boundary during peak snowmelt runoff contained the highest metal loads of any sample collected during the 1999 water year. The total-recoverable iron concentration in the June 22, 1999 sample was 6.26 mg/L (append. D).

Metal Sources

The loading of metals at different points in the stream was compared to isolate areas of surface or ground-water inflow that may be contributing metals to the stream or diluting them. The magnitude of different sources relative to the whole system also was compared. The highest inflow metal concentrations do not always indicate the most significant sources of metal loading.

Examined collectively, the metal-load profiles indicate three areas contributing most of the metals to Soda Butte Creek. The three major areas of concern are the inflows from the McLaren Mine tailings impoundment (between 505 m and 760 m), Republic Creek (1,859 m), and Unnamed Tributary (8,267 m). The McLaren mill site did not contribute to metal loading in Soda Butte Creek during the tracer-injection and synoptic-sampling study because the site was dry. However, significant rill erosion was evident at the mill site immediately upgradient of Soda Butte Creek. During the spring snowmelt season, as well as during significant summer rainstorms, the McLaren mill site probably contributes to the metal loading of Soda Butte Creek.

Results indicate that treatment or removal of the McLaren Mine tailings impoundment would greatly reduce metal loading of Soda Butte Creek upstream of YNP. However, removing only that single source may not reduce metal loads to acceptable levels. The sources of metal loading in Republic Creek and Unnamed Tributary merit further investigation.

SUMMARY

Acid drainage from historic mining activities has affected the water quality and aquatic biota of Soda Butte Creek upstream of Yellowstone National Park. A retrospective analysis of previous research on metal loading in Soda Butte Creek was completed to provide summaries of studies pertinent to metal loading in Soda Butte Creek and the effects of the loading on the water quality and aquatic biota. None of the studies conducted on Soda Butte Creek have included an examination of the effects of metal loading on the entire basin.

The research was divided into studies of surface-water quality, fluvial geomorphology, and aquatic biota. In general, the more recent studies indicate that the health of the aquatic ecosystem continues to be negatively impacted by historic mining activities. Flooding could expose buried tailings sediments, wash fresh tailings sediments into the stream, or carry metal-contaminated aquatic biota into Yellowstone National Park. Such an event would likely cause a significant increase in metal loading in Soda Butte Creek.

A critical gap in the existing data was identification and quantification of the sources of metal loading to Soda Butte Creek. Although the McLaren Mine tailings impoundment and mill site has long been identified as a source of metals, its contribution relative to the total metal load entering Yellowstone National Park was unknown. A tracer-injection and synoptic-sampling study was designed to determine metal loads in Soda Butte Creek upstream of Yellowstone National Park.

The tracer-injection and synoptic-sampling study was conducted on an 8,511-meter reach of Soda Butte Creek from upstream of the McLaren Mine tailings impoundment and mill site downstream to the Yellowstone National Park boundary in August 1999. Synoptic-sampling sites were selected to divide the creek into discrete segments. A lithium bromide tracer was added to the stream. Stream discharge values, combined with constituent concentrations obtained by synoptic sampling, were used to quantify constituent loading in each segment of Soda Butte Creek.

Much of the metal load was transported in the colloidal phase. Of particular concern are the colloidal iron hydroxides, as they accumulate on the streambed. This accumulation adversely affects the aquatic biota by altering the physical habitat of aquatic organisms. In addition, metals can sorb to the colloids and create a chronic source of toxicity (Kimball and others, 1999).

Loads were calculated for dissolved calcium, silica, and sulfate, as well as for dissolved and total-recoverable iron, aluminum, and manganese. Loads were not calculated for cadmium, copper, lead, and zinc because these elements were infrequently detected in the mainstem synoptic samples. All of these elements were detected at high concentrations in the seeps from the McLaren Mine tailings impoundment. The lack of detection of these elements in the downstream mainstem synoptic samples is probably because of sorption (coprecipitation and adsorption) to metal colloids in the stream. These results agree with those of previous studies conducted in the area. Researchers analyzing water-column samples have detected very low concentrations of these elements (Miller and others, 1997). Other researchers analyzing the aquatic biota of Soda Butte Creek have attributed a decline in stream health along this segment of the creek to elevated trace-element concentrations, particularly copper (Forstner and Wittman, 1983; Nimmo and Willox, 1996).

Most of the metal load that entered Soda Butte Creek was contributed by three areas. The three major areas of concern are the inflows that drain the McLaren Mine tailings impoundment (between 505 m and 760 m downstream from the tracer-injection site), Republic Creek (1,859 m), and Unnamed Tributary (8,267 m). The McLaren mill site did not contribute to metal loading in Soda Butte Creek during the tracer-injection and synoptic-sampling study because the site was dry. However, significant rill erosion was evident at the mill site immediately upgradient of Soda Butte Creek. During the spring snowmelt season, as well as during significant summer rainstorms, the McLaren mill site probably contributes to the metal loading of Soda Butte Creek.

Results indicate that treatment or removal of the McLaren Mine tailings impoundment would greatly reduce metal loading of Soda Butte Creek upstream of Yellowstone National Park. However, removing only that single source may not reduce metal loads to acceptable levels. The sources of metal loading in Republic Creek and Unnamed Tributary merit further investigation.

REFERENCES CITED

Bates, R.L., and Jackson, J.A., eds., 1980, Glossary of Geology, 2d ed.: Falls Church, Virginia, American Geological Institute, 749 p.

Bencala, K.E., 1984, Interactions of solutes and streambed sediments, 2, A dynamic analysis of coupled hydrologic and chemical processes that determine solute transport: Water Resources Research, v. 20, no. 12, p. 1804-1814.

Bencala, K.E., and McKnight, D.M., 1987, Identifying in-stream variability--Sampling iron in an acidic stream, *in* Averett, R.C., and McKnight, D.M., eds., Chemical Quality of Water and the Hydrologic Cycle: Chelsea, Mich., Lewis Publishers, p. 255-269.

Brinton, T.I., Antweiler, R.C., and Taylor, H.E., 1996, Method for the determination of dissolved chloride, nitrate, and sulfate in natural water using ion chromatography: U.S. Geological Survey Open-File Report 95-426A, 16 p.

Broshears, R.E., Bencala, K.E., Kimball, B.A., and McKnight, D.M., 1993, Tracer-dilution experiments and solute-transport simulations for a mountain stream, Saint Kevin Gulch, Colorado: U.S. Geological Survey Water-Resources Investigations Report 92-4081, 18 p.

Bureau of Reclamation, 1989, Analysis of corrective action alternatives for the McLaren tailings site, Cooke City, Montana, 20 pp.

_____1991, McLaren mine tailings, Soda Butte Creek - September 1990 water sample analysis review: Memorandum from J.R. Boehmke to D. Jewell, Billings, Mont., Bureau of Reclamation unpublished data.

Chadwick, J.W., 1974, The effects of iron on the macroinvertebrates of Soda Butte Creek: Bozeman, Mont., Montana State University, unpublished Master of Science thesis, 25 p., appendices.

David Stiller and Associates, 1983, Determination of public health hazards associated with the McLaren tailings pond near Cooke City, Montana: Helena, Mont., David Stiller and Associates, 32 p.

Drever, J.I., 1997, The geochemistry of natural waters: Upper Saddle River, New Jersey, Prentice Hall Publishers, 436 p.

Duff, D.A., 1972, Reconnaissance survey of aquatic habitat conditions affected by acid mine pollution in the Cooke City area, Custer and Gallatin National Forests, Montana, and Shoshone National Forest, Wyoming: U.S. Fish and Wildlife Service, Division of Range and Wildlife, Northern Region, 18 p.

Ecology and Environment, Inc., 1988, Preliminary endangerment assessment for McLaren mine tailings, Cooke City, Montana: Denver, Colo., Ecology and Environment, Inc. Technical Directive Document T08-8705-016.

Elder, J.F., 1988, Metal biogeochemistry in surface-water systems – a review of principles and concepts: U.S. Geological Survey Circular 1013, 43 p.

Elliott, J.E., 1979, Geological map of the southwest part of the Cooke City quadrangle, Montana and Wyoming: U.S. Geological Survey Miscellaneous Investigation Series Map I-1084, scale 1:24,000.

Epstein, J.L., 1997, Hydraulic aspects of the McLaren Mine tailings dam-break flood in Soda Butte Creek, Yellowstone National Park: Middlebury, Vt., Middlebury College, unpublished Bachelor of Arts thesis, 74 p.

Erickson, B.M., and Norton, D.R., 1994, Monitoring of Soda Butte Creek riparian zone, *in* Proceedings of the American Water Resources Association, June 26-29, 1994, Jackson Hole, Wyoming, [abs.]: Bethesda, Md., American Water Resources Association.

Ewing, R., 1994, Riparian landform and deposit mapping, Soda Butte Creek, northeast Yellowstone National Park: Mammoth, Wyo., National Park Service, Yellowstone National Park Division of Research, Investigator's annual reports, accessed November 25, 1999 at URL http://165.83.23.11/amoeba/resiar.nfs.

Forstner, U., and Wittman, G.T.W., 1983, Metal pollution in the aquatic environment: Berlin, Springer-Verlag, 486 p.

Glidden, R., 1982, Exploring the Yellowstone high country, a history of the Cooke City area, 2d ed.: Cooke City Mont., Cooke City Store, 120 p.

Hill, R.D., 1970, McLaren mine tailings mine drainage: Federal Water Quality Administration, Robert A. Taft Water Research Center, unpublished report, 12 p.

INTERA, Inc., 1991, McLaren tailings site, Soda Butte Creek water quality analysis: Salt Lake City, Utah, INTERA Inc., 7 p., appendices.

Kilpatrick, F.A., and Cobb, E. D., 1985, Measurement of discharge using tracers: U.S. Geological Survey Techniques of Water-Resources Investigations, book 3, chap. A16, 52 p.

Kimball, B.A., 1996, Use of tracer injections and synoptic sampling to measure metal loading from acid mine drainage: U.S. Geological Survey Fact Sheet FS-245-96, 4 p.

Kimball, B.A., Callender, E., and Axtmann, E.V., 1995, Effects of colloids on metal transport in a river receiving acid mine drainage: Environmental Science and Technology, v. 28, p. 2065-2073.

Kimball, B.A., Runkel, R.L., and Gerner, L.J., 1998, Quantification of metal loading in French Gulch, Summit County, Colorado, using a tracer-injection study, July 1996: U.S. Geological Survey Water-Resources Investigations Report 98-4078, 38 p.

Kimball, B.A, Nimick, D.A., Gerner, L.J., and Runkel, R.L., 1999, Quantification of metal loading in Fisher Creek by tracer-injection and synoptic sampling, Park County, Montana, August 1997: U.S. Geological Survey Water-Resources Investigations Report 99-4119, 43 p.

Ladd, S.C., 1995, Channel morphology controls on the spatial distribution of trace metals in bed sediments in Soda Butte Creek, Montana: Bozeman, Mont., Montana State University, unpublished Master of Science thesis, 83 p.

Mahoney, Dan, 1996, Effects of acidic mine waters on the aquatic invertebrates community of Soda Butte Creek: Mammoth, Wyo., National Park Service, Yellowstone National Park Fisheries Program, Investigator's annual reports, assessed November 26, 1999 at URL http://165.83.23.11/amoeba/resiar/nfs.

Marchand, J.P., Jarrett, R.D., and Jones, L.L., 1984, Velocity profile, water-surface slope, and bed-material size for selected streams in Colorado: U.S. Geological Survey Open-File Report 84-733, 82 p.

Marcus, W.A., 1997, Morphologic controls on multiscale distributions of mining-derived trace metals in riparian sediments, resultant biotic impacts, and implications for monitoring and remediation: Bozeman, Mont., 18th annual meeting, Society of Wetland Sciences, monograph.

Marcus, W.A., Meyer, G.A., and Nimmo, D.R., 2001, Geomorphic control of persistent mine impacts in a Yellowstone Park stream, and implications for the recovery of fluvial systems: Geology, v. 29, no. 4, p. 355-358.

Marcus, W.A., Stroughton, J.A., Ladd, S.C., and Richards, D., 1995, Trace metal concentrations in sediments and their ecological impacts in Soda Butte Creek, Montana and Wyoming, *in* Meyer, Grant, ed., Late-Pleistocene-Holocene evolution of the northeastern Yellowstone landscape: Middlebury Vt., Middlebury College, Friends of the Pleistocene - Rocky Mountain Cell 1995 field conference guidebook, 9 p.

Mason, B., 1966, Principles of geochemistry: New York, John Wiley and Sons, Inc., 329 p.

Maxim Technologies, 1999, New World Mining District response and restoration project: accessed November 11, 1999 at URL http://www.maximtechnologies.com/newworld/.

McKnight, D.M., and Feder, G.L., 1984, The ecological effect of acid conditions and precipitation of hydrous metal oxides in a Rocky Mountain stream: Hydrobiology, v. 119, no. 2, p. 129-138.

Meyer, G.A., 1993, A polluted flash flood and its consequences: Yellowstone Science, v.3, no. 1, p. 2-6.

Meyer, G.A., and Watt, P.M., 1998, Mine tailings contamination of floodplain sediments in Yellowstone National Park: National Geographic Society grant #5699-96.

Miller, W.R., A.L. Meier, and P.H. Briggs, 1997, Geochemical processes and baselines for stream waters for Soda Butte-Lamar basin and Firehole-Gibbon basin, Yellowstone National Park: U.S. Geological Survey Open-File Report 97-550, 27 pp.

Mills, L.E., and Sharpe, F.P., 1968, Pollution study of Soda Butte Creek, Yellowstone National Park, Wyoming, [unpublished mimeograph]: Ft. Collins, Colo., U.S. Department of the Interior, Bureau of Sport Fisheries and Wildlife, Division of Fishery Services, 16 p.

Montana Bureau of Mines and Geology, 1999,Hydrogeology of the upper Soda Butte Creek Basin, Montana: Butte, Mont., Montana Bureau of Mines and Geology, Report of Investigation 7, 66 p.

Nimmo, D. R., Willox, M.J., 1996, Seasonal liabilities from the McLaren tailings on aquatic resources in Soda Butte Creek and Yellowstone National Park, *in* Nelson, J.D., and others, eds., Proceedings of the Third Interagency Conference on Tailings and Mine Waste, Fort Collins, Colorado: Rotterdam, The Netherlands, Balkema Publishing, p. 415-420.

Nimmo, D.R., Willox, M.J., LaFrancois, T.D, Chapman, P.L., Brinkman, S.F., and Greene, J.C., Brinkman, S.F., 1998, Effects of metal mining and milling on boundary waters of Yellowstone National Park, USA: Environmental Management, v. 22, no. 6, p. 913-926.

Omang, R.J., Parrett, Charles and Hull, J.A., 1983, Flood estimates for ungaged streams in Glacier and Yellowstone National Parks, Montana: U.S. Geological Survey Water-Resources Investigations Report 83-4147, 10 p.

Pickett, F.J., and Chadwick, J.W., 1972, Studies on Soda Butte, Slough, and Iron Springs Creeks, Yellowstone National Park: Bozeman, Mont., Montana State University, Final report for contract 2-101-0387, 54 p.

Pierce, W.G., Nelson, W.H., and Prostka, H.J., 1973, Geologic map of the Pilot Peak quadrangle, Park County, Wyoming: U.S. Geological Survey Miscellaneous Geologic Investigations Map I-816, scale 1:62,500.

Rantz, S.E., and others, 1982a and 1982b, Measurement and computation of Streamflow—v. 1, Measurement of stage; v. 2, Computation of discharge: U.S. Geological Survey Water-Supply Paper 2175, v. 1, 284 p.; v. 2, 346 p.

Runkel, R.L., Kimball, B.A., McKnight, D.M., and Bencala, K.E., 1999, Reactive solute transport in stream--A surface complexation approach for trace metal sorption: Water Resources Research, v. 35, no. 12, p. 3829-3840.

Stoughton, Julie, 1995, The impacts of trace metals on grassland communities along the floodplain of Soda Butte Creek: Bozeman, Mont., Montana State University, unpublished Master of Science thesis, 109 p.

Swanson, R.B., Smalley, M.L., Woodruff, R.E., and Clark, M.L., 2000, Water-resources data, Wyoming, water year 1999, volume 1. Surface Water: U.S. Geological Survey Water-Data Report, WY-99-1, 484 p.

Theobald, P.K., Jr., Lakin, H.W., and Hawkins, D.B., 1963, The precipitation of aluminum, iron and manganese at the junction of Deer Creek with the Snake River in Summit County, Colorado: Geochimica et Cosmochimica Acta, v. 27, no. 2, p. 121-132.

U.S. Environmental Protection Agency, 1971, Baseline water quality survey report-Yellowstone National Park: Kansas City, Mo., U.S. Environmental Protection Agency, Region VII.

_____1972, Personal correspondence, John A. Green, regional administrator, Denver, Colorado, to Donald G. Willems, chief, Montana Water Quality Bureau, 30 pp.

_____1989, Request for removal action approval at the McLaren tailings site, Cooke City, Montana: action memorandum NPL site id #93, 7 p.

Velleman, P.F., and Hoaglin, D.C., 1981, Applications, basics, and computing of exploratory data analysis: Boston, Mass., Duxbury Press, 354 p.

Wilson, J.F., and Rankl, J.R., 1996, Use of dye tracing in water-resources investigations in Wyoming, 1967-94: U.S. Geological Survey Water-Resources Investigations Report 96-4122, 64 p.

Wright, A., 1998, The use of multispectral digital imager to map hydrogeomorphic stream units in Soda Butte and Cache Creeks, Montana and Wyoming: Bozeman, Mont., Montana State University, unpublished Master of Science thesis, 76 p.

Zellweger, G.W., Avanzino, R.J., and Bencala, K.E., 1989, comparison of tracer-dilution and current-meter discharge measurements in a small gravel-bed stream, Little Lost Man Creek, California: U.S. Geological Survey Water-Resources Investigations Report 89-4150,
20 p.

Zellweger, G.W., Bencala, K.E., McKnight, D.M., Hirsch, R.M., and Kimball, B.A., 1988, Practical aspects of tracer experiments in acidic, metal enriched streams, i*n* Mallard, G.E., ed., U.S. Geological Survey Toxic Substances Hydrology Program—Surface-Water Contamination: U.S. Geological Survey Open-File Report 87-764, p. 125-130.

APPENDIX A

ANNOTATED BIBLIOGRAPHY OF PREVIOUS RESEARCH ON METAL LOADING IN SODA BUTTE CREEK, MONTANA AND WYOMING

Note: Most annotations are quoted from cited references. Minor editing of some annotations was done to improve clarity.

Annotated Bibliography

Anderson, J.R., 1995, Stream terraces of lower Soda Butte Creek, northeastern Yellowstone National Park: Middlebury, Vt., Middlebury College, unpublished Bachelor of Arts thesis, 35 p.

Badon, N.M., and Schrader, E.L., 1999, Preliminary geochemical study of Soda Butte Creek in Yellowstone National Park: Jackson, Miss., Journal of the Mississippi Academy of Sciences, v. 44, no. 1, p. 47-48.

Bureau of Reclamation, 1989, Analysis of corrective action alternatives for the McLaren tailings site, Cooke City, Montana: Billings, Mont., Bureau of Reclamation, Great Plains Region, 20 p.

Presentation of investigation results, data interpretation (site characterization) and analysis of corrective action alternatives for the McLaren tailings site near Cooke City, Montana. Report provides the technical basis for developing a full Engineering Evaluation/Cost Analysis (EE/CA) should the need for such a document be identified in the future. A number of alternatives were listed for dealing with four problems: runoff and seepage from the old mill and ore storage areas, flooding of Soda Butte Creek, tailings dam failure, and seepage from the tailings and tailings dam. No alternatives recommended.

_____1991, McLaren mine tailings, Soda Butte Creek - September 1990 water sample analysis review: Memorandum from J.R. Boehmke to D. Jewell, Billings, Mont., Bureau of Reclamation unpublished data.

A total of 22 samples were taken. Of 25 elements analyzed, 5 (Cd, Pb, Cu, Zn, and Fe) were chosen as elements that could potentially have an impact upon the aquatic life in Soda Butte Creek. One value exceeded the freshwater aquatic-life criterion for copper. In general, copper does not appear to be of concern to the aquatic environment in Soda Butte Creek, although certain conditions may initiate high concentrations. Iron concentrations were above the detection limit more often than other elements. It is the only element evaluated that consistently showed higher concentrations below the mine tailings, compared to the concentrations above the tailings. The iron concentration is high enough to cause iron precipitate to form on the stream substrate. This appears to have prevented the full utilization of the substrate by aquatic invertebrates, thereby reducing a major food source for the fish species inhabiting the reach of Soda Butte Creek below the tailings area.

Carolan, G. F., 1997a, Distribution and geochemistry of tailings contaminated floodplain sediments along Soda Butte Creek, Yellowstone National Park, Montana-Wyoming: Middlebury, Vt., Middlebury College, unpublished Bachelor of Arts thesis, 83 p.

_____1997b, Distribution and geochemistry of tailings contaminated floodplain sediments along Soda Butte Creek, Yellowstone National Park, Montana-Wyoming: The Green Mountain Geologist, v. 24, no. 2, spring 1997

The McLaren tailings impoundment is a significant source of acid drainage containing metals. Dissolved-copper concentrations in the water were highest during spring runoff. Floodplain tailings may be another significant source of trace-metal pollution.

Chadwick, J.W., 1974, The effects of iron on the macroinvertebrates of Soda Butte Creek: Bozeman, Mont., Montana State University, unpublished Master of Science thesis, 25 p., appendices.

Dissolved iron from the McLaren tailings is the primary water-quality problem affecting macroinvertebrates of Soda Butte Creek. Soda Butte Creek experiences substantial seasonal differences in discharge, which have been measured to be 20 times greater during spring runoff than in the fall.

Chaffee, M.A., Hoffman, J.D., and Tidball, R.R., 1995, Stream-sediment geochemistry in the Soda Butte Creek watershed in comparison to the surrounding region in Montana and Wyoming--Proceedings of the Second International Conference on Tailings and Mine Waste, Fort Collins, Colorado: Rotterdam, The Netherlands, Balkema Publishing,

Chaffee, M.A., 1998, Environmental geochemistry in Yellowstone National Park--Distinguishing natural and anthropogenic anomalies: Yellowstone Science, Agenda and Abstracts, 125th anniversary symposium, v. 6, no. 2, p. 29.

Clancy, C., Bureau of Reclamation, written commun., 1988: Billings, Montana, Personal communication with J. Boehmke, Montana Department of Fish, Wildlife, and Parks, Bureau of Reclamation.

Personnel from the Montana Department of Fish, Wildlife, and Parks electrofished Soda Butte Creek in October 1985. Two stations were shocked, one 500 feet upstream from the mouth of Sheep Creek and the other a 400-foot stretch near Silver Gate. The Sheep Creek station yielded 26 cutthroat ranging from 7.6 to 11.6 inches in length, and averaging about 1/3 pound. The Silver Gate station yielded 18 cutthroat trout ranging from 6.1 to 10.1 inches in length, and averaging about 1/4 pound.

Davenport, P., 1972, Iron and the pollution problem in Yellowstone National Park.

David Stiller and Associates, 1983, Determination of public health hazards associated with the McLaren tailings pond near Cooke City, Montana: Helena, Mont., David Stiller and Associates, 32 p.

At the request of the Abandoned Mine Reclamation Bureau, Montana Department of State Lands, a study was conducted to ascertain the possibility of contamination of domestic water supplies near Cooke City, Montana. The majority of Cooke City residents obtain their water from a spring-fed holding tank above the valley 1/8 mile northwest of town. Soda Butte Creek loses a large quantity of its flow to the McLaren tailings throughout the year. Because of this, it is anticipated that the Soda Butte Creek alluvial aquifer downgradient from this site may be impacted by highly mineralized ground water emanating from the shallow McLaren tailings aquifer. The extent and magnitude of this contamination is unknown. No significant contamination of domestic water resources was identified during this investigation, other than elevated iron concentrations in surface water samples obtained from Woody Creek and Soda Butte Creek below the tailings.

Decker-Hess, J., and White, R.G., 1987, In-stream flow requirements of Soda Butte Creek, Yellowstone National Park: Bozeman, Mont., Montana Cooperative Fish Research Unit, Montana State University, 30 p.

Instream flow requirements were determined for Soda Butte Creek, Yellowstone National Park using the Montana Department of Fish, Wildlife and Parks wetted perimeter/inflection-point method. Previous data collected on the physical description of the creek, its water quality, macroinvertebrate and fisheries populations and other data were summarized. Management recommendations based on literature review and current conditions were formulated. Instream flow requirements for upper Soda Butte Creek were a minimum flow of 13 cfs and an optimum flow of 24 cfs, and for lower Soda Butte Creek, 46 cfs minimum and 58 cfs optimum. Based on an evaluation of fishery data, recreational use, current condition and other resource information, a minimum flow of 20 cfs and an optimum flow of 58 cfs were recommended for Soda Butte Creek at the Northeast Entrance and the Lamar River Trail bridge.

Duff, D.A., 1972, Reconnaissance survey of aquatic habitat conditions affected by acid mine pollution in the Cooke City area, Custer and Gallatin National Forests, Montana, and Shoshone National Forest, Wyoming: U.S. Fish and Wildlife Service, Division of Range and Wildlife, Northern Region, 18 p.

Runoff and seepage from the McLaren tailings to Soda Butte Creek are adversely impacting the creek ecosystem. No fish are present in Soda Butte Creek below the tailings site for 3 miles.

Ecology and Environment, Inc., 1987, McLaren mill tailings endangerment review, Cooke City, Montana: Denver, Colo., Ecology and Environment, Inc. Technical Directive Document F08-8612-03, draft report, 30 p.

There is a concern that valley residents are consuming water from domestic wells completed in alluvial deposits downgradient of the tailings pile. A health threat may exist and needs to be explicitly determined. Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) environmental threats may be present and affect riparian wetlands and aquatic life. The tailings qualify for evaluation as a Special Studies Waste under the Superfund Amendments and Reauthorization Act (SARA) and a site investigation (SI) is warranted. An SI would include drilling of monitor wells in alluvial aquifer upgradient and downgradient of tailings, tailings sampling to determine metals concentrations and hazardous waste quantity under definition of special-study wastes, sediment sampling and benthic studies of Soda Butte Creek to evaluate contaminant migration and environmental impact, and surface-water sampling to document a contaminant release.

_____1988, Preliminary endangerment assessment for McLaren mine tailings, Cooke City, Montana: Denver, Colo., Ecology and Environment, Inc. Technical Directive Document T08-8705-016.

Surface-water quality samples analyzed showed only iron concentrations are occurring at levels that are toxic to aquatic life (1,020 µg/L at station MCSW-5 and 2,850 µg/L at station MCSW-6).

Elliott, J.E., Kirk, A.R., and Johnson, T.J., 1979, Field guide--Gold-copper-silver deposits of the New World District: Crown Butte Mines, Inc., unpublished report, 19 p.

Environmental Response Team, 1988, McLaren tailings--Evaluation of four alternatives for a removal action: Edison, N.J., Environmental Response Team Technical Directive Document T08-8802-024, variable pagination.

Release of heavy-metal laden leachates from the McLaren mill site has been well documented. Their transport off-site and into nearby Soda Butte Creek is clearly evident by the pronounced discoloring of the streambed. Environmental samples have quantified this contamination (Ecology and Environment, Inc., 1988). The instability of the tailings has been evaluated and confirmed (Maddox, 1983). The failure of the tailings under Probable Maximum Flood conditions has been predicted (Womack, 1984). Tailings failure would also induce a secondary, less direct, adverse effect upon the local economies of Cooke City and Silver Gate. These local economies rely heavily on tourism generated by the ideal environment of YNP. For the above reasons, it is concluded that the risks posed to the environment and public welfare by the McLaren tailings site justify a Removal Action. The feasibility of four removal action alternatives is examined.

Epstein, J.L., 1997, Hydraulic aspects of the McLaren Mine tailings dam-break flood in Soda Butte Creek, Yellowstone National Park: Middlebury, Vt., Middlebury College, unpublished Bachelor of Arts thesis, 74 p.

In June 1950 the McLaren impoundment failed, flushing pyritic tailings down the Soda Butte floodplain. The tailings were deposited as overbank sediments with thickness up to at least 60 cm. The tailings contain high concentrations of heavy metals such as copper and lead, which now impact the river ecosystem. This study was conducted to evaluate the hydraulic aspects of the tailings flood.

Epstein, J.L., and Meyer, G.A., 1997, Hydraulic aspects of the McLaren Mine tailings dam-break flood in Soda Butte Creek, Yellowstone National Park (abs.): Geological Society of America, Abstracts with Programs, v. 29, no. 1, p. 43.

Erickson, B.M., and Norton, D.R., 1994, Monitoring of Soda Butte Creek riparian zone, *in* Proceedings of the American Water Resources Association, June 26-29, 1994, Jackson Hole, Wyoming, [abs.]: Bethesda, Md., American Water Resources Association.

Riparian vegetation (grass, horsetail, and willow) showed greater concentrations of copper, lead, and zinc immediately downstream of the tailings than upstream, with concentrations decreasing downstream towards the Park boundary.

Ewing, R., 1991, 1992, 1993, 1994, Riparian landform and deposit mapping, Soda Butte Creek, northeast Yellowstone National Park: Mammoth, Wyo., National Park Service, Yellowstone National Park Division of Research, Investigator's annual reports, accessed November 25, 1999, at URL http://165.83.23.11/amoeba/resiar.nsf.

Objective: Project will map fluvial deposits and landforms in the riparian and near-riparian areas of Soda Butte Creek in northeast Yellowstone National Park and the adjacent Gallatin National Forest. Information on fluvial deposits and landforms on the major Willow Study plots will be gathered to determine preferred substrates and landforms for Yellowstone National Park willow species. Deposit/landform maps will be made of the riparian zones for further riparian plant and ecological studies. Study will use black-and-white, color, and color infrared aerial photography supplemented by extensive soil coring to map Soda Butte Creek.

1991 Findings and status: None.

1992-94 Findings and status: None. Project incomplete. Investigator's term of employment ended, no further funding available.

Ewing, T.T., 1997a, Particle size variations and metals in flood-deposited mine tailings along Soda Butte Creek, Yellowstone National Park: Middlebury, Vt., Middlebury College, unpublished Bachelor of Arts thesis, 103 p.

_____1997b, Particle size variations and metals in flood-deposited mine tailings along Soda Butte Creek, Yellowstone National Park: Green Mountain Geologist, v. 24, no. 2, p. 13.

Defines the stratigraphy of the deposits and variations in particle size with depth, examines changes in particle size of tailings deposits with distance of transport, and examines relation of texture to metals concentrations.

Forstner, U., and Wittman, G.T.W., 1983, Metal pollution in the aquatic environment: Berlin, Springer-Verlag, 486 p.

Although all metals found in water or sediment from Soda Butte Creek can be toxic, copper has been shown to be the most toxic to aquatic life.

Glidden, R., 1982, Exploring the Yellowstone high country, a history of the Cooke City area, 2d ed.: Cooke City, Mont., Cooke City Store, 120 p.

Since the 1860s, prospectors have been seeking minable quantities of metals in south-central Montana. In the vicinity of Soda Butte Creek, multiple gold, silver, and copper deposits were discovered and several mines and smelters were developed. The area became known as the New World or Cooke City Mining District. The McLaren mine produced 2,000 short tons (1,814 metric tons) of copper and 60,000 troy ounces (1,866 kg) of gold between 1933 and 1940.

Green, J.A., written commun., 1972, Personal correspondence from Region VIII Administrator: Denver, Colo., U.S. Environmental Protection Agency.

In 1969, Soda Butte Creek was rerouted around the north edge of the impoundment. The tailings were leveled, graded, covered with a 0.5-1.5 meter thickness of alluvial sand and gravel, and seeded with grass.

Green, V.A., U.S. Environmental Protection Agency, written commun., 1972, Memorandum to Donald G. Willems regarding Yellowstone National Park, Baseline water quality report: Kansas City, Mo., U.S. Environmental Protection Agency, Region VII, 30 p.

Copper and zinc concentrations in Soda Butte Creek could reach undesirable levels and be a detriment to aquatic life.

Hill, R.D., 1970, McLaren mine tailings mine drainage: Federal Water Quality Administration, Robert A. Taft Water Research Center, unpublished report, 12 p.

The McLaren mine and mill are located east of Cooke City, Montana, adjacent to Soda Butte Creek. The mine was established in 1933 and operated until January 1953. At one time it was the largest operating gold mine in Montana. Some copper and silver were also mined. A large tailings area was developed next to the mill. Serious erosion of the tailings began about 1957, the sediment washing into Soda Butte Creek. The cyanide process was used in the mill. Prior surveys have shown that the fish production of Soda Butte Creek is poor. Causes of this condition have been suggested as: (1) sediment on stream bed, (2) toxic material from the tailings area, and (3) iron precipitates on streambed. The streambed of Soda Butte Creek from just below the tailings area to the entrance of Yellowstone National Park, some 4 1/2 miles, has the typical "rusty" colored iron precipitate.

The McLaren mine tailings area is responsible for a decrease in pH and alkalinity and an increase in conductivity, hardness, SO_4, Fe, Mn, Zn, and Cu concentrations.

_____1977, Mine drainage control from metal mines in a subalpine environment - a feasibility study: Cincinnati, Ohio, U.S. Environmental Protection Agency report EPA 600/2-77-224, 149 p.

The mill area is underlain by moraine deposits of Pleistocene age covered with a thin veneer of recent stream deposits. 14.5 meters of gravel below the tailings and above bedrock were encountered in one drill hole. The thickness of the gravel at this location places serious engineering constraints upon any attempts to flood the tailings pond or to dam the tailings and gravel, preventing ground water within the tailings from passing through the gravel. Tailings consist of phyllosilicates (clays), tectosilicates (predominantly feldspars and quartz), sulfides (mostly pyrite), iron oxides (magnetite, geothite, and ferric hydroxide), and calcium salts (gypsum and calcite). Investigated several remediation options including removing the tailings, treating the effluent from the tailings pile, and infiltration control by resealing the dam on the lower end of the tailings pile.

Holmes, M.A., 1995, Treatability study, McLaren tailings site, Cooke City, Montana: U.S. Environmental Protection Agency Contract No. 68-C4-0022, Final report.

INTERA, Inc., 1991, McLaren tailings site, Soda Butte Creek water quality analysis: Salt Lake City, Utah, INTERA Inc., 7 p., appendices.

McLaren tailings site is under a two-part EPA administrative order for corrective action. First action–dam stabilization–was completed by Kennecott in September 1990. Second action–dewatering of the tailings–has been ordered to be completed by October 31, 1991. It appears that in the past, discharges of tailings material entered the creek, resulting in precipitation of iron material to the stream bottom. This quite insoluble material coated the stream gravels and filled the spaces between rocks, rendering the stream bottom inhospitable to organisms and spawning fish. Therefore, a section of Soda Butte Creek below the tailings became unsuitable for trout habitat. Since then the causes of these discharges have been corrected and the water quality has improved. Iron precipitate remains on the stream rocks below the tailings because it is very insoluble and has yet to be washed away. This will occur naturally, however, and the stream will continue to return to natural trout stream conditions whether the tailings are dewatered or not. From a stream quality perspective, therefore, there is no reason to undertake a disruptive and costly dewatering project at the McLaren tailings site.

Johnson, T.W., 1994, Au-Cu-Ag skarn and replacement mineralization in the McLaren deposit, New World District, Park County, Montana: Economic Geology, v. 89, no 54, p. 969-993.

Elevated levels of trace metals in stream sediments can originate from a number of sources, including highly mineralized Eocene volcanics and Cambrian sediments above Cooke City.

Keigley, R.B., 1993, Distribution and population dynamics of exotic plants on the Soda Butte floodplain: Mammoth Hot Springs, Wyo., National Biological Service Greater Yellowstone Field Station, Investigator's annual report, accessed November 21, 1999 at URL http://165.83.23.11/amoeba/resiar.nsf,

Objective: To determine the effect of different forms of vegetation on the sediment deposited during annual flooding.

Findings: During the 1993 field season, the author found evidence that the depositional environment of Soda Butte Creek may have changed in the recent past. Specifically, there is lichenometric evidence of a 50-centimeter drop in flood stage that may have been caused by either entrenchment or by an increase in width-to-depth ratio. A preliminary survey suggests that there has been a change in the texture of sediment recently deposited during flood events. If further study supports these observations, these changes in fluvial processes have major ecologic implications.

_____1994, Relationships between fluvial landforms and riparian vegetation in the Soda Butte drainage.

Kennecott Corporation, 1990, Workplan for remediation of the McLaren tailings site, Cooke City, Montana: Kennecott Corporation.

The McLaren tailings site has been designated an emergency response action site by EPA region VIII. Kennecott Corporation was named a potentially responsible party (PRP). Kennecott reviewed the corrective action plan and elected to manage and perform the corrective actions at the site in lieu of the Bureau of Reclamation. Kennecott retained the geotechnical firm of Sergent, Hauskins, and Beckwith (SHB) to conduct an independent stability analysis of the McLaren tailings dam. SHB concluded that the dam is stable, both statically and dynamically, with an adequate factor of safety, and therefore further stability work on the dam is not warranted. Runoff is to be collected and diverted around the tailings in a diversion channel constructed immediately upslope of the tailings. Kennecott and its contractors believe a portion of the high iron content in the water below the dam is a result of water coming into contact with the relatively small amount of tailings deposited below the tailings dam. Kennecott plans to make a best-effort attempt to excavate the bulk of the tailings deposited below the dam and deposit them in the tailings area behind the dam.

Kerr, M., written commun., 1986, Soda Butte Creek survey: November 13, 1986 office memorandum to the Montana State Department of Health and Environmental Sciences, 12 p.

The channel bottom was "cemented" for about 1.6 km downstream of the tailings in a reach where only a few small trout were evident.

Knudson, K., and Estes, C., 1975, Biological study, acid-mine control feasibility study, Cooke City, Montana: Montana Department of Fish and Game report, May-October, 1975, 33 p.

In 1969, Soda Butte Creek was rerouted around the north edge of the impoundment. The tailings were leveled, graded, covered with a 0.5-1.5 meter thickness of alluvial sand and gravel, and seeded with grass.

Ladd, S.C., 1995, Channel morphology controls on the spatial distribution of trace metals in bed sediments in Soda Butte Creek, Montana: Bozeman, Mont., Montana State University, unpublished Master of Science thesis, 83 p.

Consistent and statistically significant changes in copper concentrations occur at the scale of the individual morphological units.

Ladd, S.C., Marcus, W.A., and Cherry, S., 1997, Trace mineral segregation within morphological units in Soda Butte Creek: Environmental Geology and Water Sciences, v. 36, no. 3, p. 195-206.

Landis, J.D., and Meyer, G.A., 1997, Recent debris-flow and flash-flood history of northeastern Yellowstone National Park: Green Mountain Geologist, v. 24, no. 2, p. 15-16.

Lynn, S.V., U.S. Geological Survey, written commun., 1998: Helena, Mont., U.S. Geological Survey memorandum.

The 1996 peak discharge of about 2,450 ft3/s deposited overbank sediments up to a few decimeters below the highest tailings deposits.

Maddox, G.E., 1983, Evaluation of stability of tailings dam and peak flow for channel design, McLaren mill tailings project, Cooke City, Montana: Spokane, Wash., George Maddox and Associates, Inc., 20 p.

Stability of the McLaren Mine tailings was investigated. The 50-year flood was estimated to be 1,226 cubic feet per second (cfs), and the 100-year flood to be 1,665 cfs. Four of five failure surfaces analyzed had a safety factor of less than one. Determined that dam failure is "imminent."

Mahoney, Dan, 1992, 1993, 1994, 1995, 1996, Effects of acidic mine waters on the aquatic invertebrates community of Soda Butte Creek: Mammoth, Wyo., National Park Service, Yellowstone National Park Fisheries Program, Investigator's annual reports, accessed November 26, 1999 at URL http://165.83.23.11/amoeba/resiar.nsf.

Objective [1992]: To monitor the water quality of a 7-kilometer stretch of Soda Butte Creek immediately upstream from the northeast entrance of Yellowstone National Park which has been polluted from acid mine drainage waters from the tailings heap of the abandoned McLaren gold mine near Cooke City, Montana.

Objective [1993-96]: To assist the National Park Service in the interpretation of data on macroinvertebrates and fishes in Soda Butte Creek, a stream affected by acidic mine waters from the tailings of the abandoned McLaren gold mine, Cooke City, MT.

1992-93 Findings and Status: Pollution effects are severe immediately downstream of the tailings, but stream conditions improve gradually in a downstream direction.

1994-96 Findings and Status: Pollution effects, though severe immediately downstream from the tailings, have been reduced in recent years as the result of efforts to better contain the tailings and prevent seepage of acidic waters.

Mangum, F.A., 1984, Aquatic ecosystem inventory macroinvertebrate analysis: U.S. Department of Agriculture-Forest Service, Intermountain Region Aquatic Ecosystem Analysis Laboratory, Brigham Young University, Provo, Utah, Annual progress report.

_____1986, Aquatic ecosystem inventory macroinvertebrate analysis: U.S. Department of Agriculture-Forest Service, Intermountain Region Aquatic Ecosystem Analysis Laboratory, Brigham Young University, Provo, Utah, Annual progress report, 6 p.

Biological indices of macroinvertebrate community health in Soda Butte Creek downstream from the tailings were lower than those of similar streams in this region between 1984 and 1986 and, "there appeared to be stress conditions [to macroinvertebrates] at each of the sampling stations," including one located about 1.6 kilometers within Yellowstone National Park.

_____1987, Aquatic ecosystem inventory macroinvertebrate analysis: U.S. Department of Agriculture-Forest Service, Intermountain Region Aquatic Ecosystem Analysis Laboratory, Brigham Young University, Provo, Utah, Annual progress report.

_____1991, 1992, 1993a, 1994, Aquatic ecosystem analysis for Soda Butte Creek (macroinvertebrate and water quality): Mammoth Hot Springs, Wyo. U.S. Fish and Wildlife Service, Yellowstone National Park, Annual progress report, accessed November 26, 1999 at URL http://165.83.23.11/amoeba/resiar.nsf,

Objective: To monitor pollution from the McLaren Mine tailings in Cooke City.

1991-94 Findings and status: None.

_____1993b, Aquatic ecosystem inventory, macroinvertebrate analysis: U.S. Department of Agriculture-Forest Service, Intermountain Region Aquatic Ecosystem Analysis Laboratory, Brigham Young University, Provo, Utah, Annual progress reports, 1991-1992.

Results from another study with data from sampling stations located immediately upstream from the boundary of YNP indicated that there could be effects from both mine tailings and tributary stream waters, since many of the tributaries drain old abandoned mines.

Macroinvertebrate indices improve downstream of the Park boundary, but there appears to be some opportunity for management to improve water quality and instream habitat quality.

Marcus, W.A., 1995, Research on trace metal concentrations in sediments and their impacts in Soda Butte Creek, Montana and Wyoming: Interagency meeting on Soda Butte Creek watershed, Mammoth, Wyo., Monograph.

_____1997, Morphologic controls on multiscale distributions of mining-derived trace metals in riparian sediments, resultant biotic impacts, and implications for monitoring and remediation: Bozeman, Mont., 18th annual meeting, Society of Wetland Sciences, Monograph.

Metals vary between riffles, pools, bars, and glides. Macroinvertebrate populations generally increase in number and diversity with increasing distance downstream from Cooke City. The primary control on metal concentrations and variability in upper reaches of the stream appears to be related to oxide coatings on the sediment.

Marcus, W.A., and Ladd, S.C., 1995, Reach scale spatial variability of trace metal concentrations in channel bed sediments, Soda Butte Creek, Montana: Bozeman, Mont., Geological Society of American, Rocky Mountain section, Monograph.

Marcus, A.D, Ladd, S.C., and Crotteau, M., 1996, Channel morphology and copper concentrations in stream bed sediments, *in* Nelson, J.D., and others, eds., Proceedings of the Third International Conference on Tailings and Mine Waste, Fort Collins, Colorado., USA: Rotterdam, The Netherlands, Balkema Publishing, p. 421-430.

Metals are segregated into discrete subpopulations within morphologic units such as riffles, pools, and glides. Sediment metal concentrations decreased with distance from the tailings in high gradient riffles and glides but in some backwater pool sediment, copper was higher far downstream of the tailings than immediately below them. Some of the highest concentrations of copper were inside the park boundary. Typically, the silt-clay fractions contained the most copper but the coarser 1-2 millimeter fraction often contained the next highest concentrations.

Marcus, W.A., Stoughton, J.A., Ladd, S.C., and Richards, D., 1995, Trace metal concentrations in sediments and their ecological impacts in Soda Butte Creek, Montana and Wyoming, *in* Meyer, Grant, ed., Late-Pleistocene-Holocene evolution of the northeastern Yellowstone landscape: Middlebury Vt., Middlebury College, Friends of the Pleistocene - Rocky Mountain Cell 1995 field conference guidebook, 9 p.

Research by author began in 1993, focusing on characterizing the range of spatial and temporal variability in trace-metal concentrations in active channel sediments, explaining the processes controlling that variability, and documenting the impacts (if any) of trace-metal concentrations on biotic populations.

Trace metal concentrations in the stream bed generally decrease downstream as a function of dilution mixing with clean sediments from tributaries. Local scale metal variations in riffles, pools, and bars vary as a function of sediment size and perhaps as a function of residence time and resultant accumulation of iron oxides. Biodiversity within the stream improves downstream, but has shown little improvement over the last 50 years. In contrast, some biotic impacts in the floodplain 20 kilometers downstream are as severe as those at the tailings site. The amount of impacted area in the floodplain, however, is slowly improving over time as contaminated sediments are removed by floods.

_____1998, Geomorphic controls on long-term biotic response to sediment contamination from mining in the stream and floodplain zones of Soda Butte Creek (abs.): Yellowstone Science, v. 6, no. 2, 39 p.

Marcus, W.A., Meyers, G.A., and Nimmo, D.R., 2001, Geomorphic control of persistent mine impacts in a Yellowstone Park stream and implications for the recovery of fluvial systems: Geology, v. 29, no. 4, p. 355-358.

A half-century after mine closure, metal contamination from sulfide ore mining in the headwaters continues to impair riparian vegetation and aquatic macroinvertebrates along Soda Butte Creek, Yellowstone National Park. A tailings dam failure in 1950 emplaced metal-rich sediment at high floodplain levels, above 50 yr to 100 yr flood stages in 1996 and 1997. These large natural floods removed only a small part of the contaminated sediment through bank erosion; they also failed to lower in-channel copper concentrations, because increased erosion of mine waste during high flows balances increased inputs of uncontaminated sediments, generating no net change in concentrations. Geomorphic processes controlling movement of contaminated sediments indicate that mine impacts will persist for centuries in Soda Butte Creek and imply long-lasting impacts in similarly affected streams worldwide.

Maxim Technologies, 1999, New World Mining District response and restoration project: Accessed November 11, 1999 at URL http://www.maximtechnologies.com.newworld/.

This web site has been provided by the Gallatin National Forest to disseminate information, reports, and data for the New World Mining District response and restoration project. It includes such features as project status, schedule, description, background, contacts, and other general information. From this site you will be able to access project reports, documents, maps and key data sets. All relevant reports prepared through the duration of this project will be posted to the site.

Merritt, R.W., and Cummins, K.W., 1996, An introduction to the aquatic insects of North America, 3rd ed.: Dubuque, Iowa, Kendall Hunt Publishers, 862 p.

In the fall of 1995, replicate samples of macroinvertebrates at each site were collected to assess metal uptake and to analyze community structure.

Metesh, John, English, Alan, Lonn, Jeff, Kendy, Eloise, and Parrett, Charles, 1999, Hydrogeology of the upper Soda Butte Creek basin, Montana: Billings, Mont., Montana Bureau of Mines and Geology, 66 p., 1 sheet.

Compilation of existing hydrogeological data. Evaluation of ground-water and water-quality relationships with respect to ground-water development in the area.

Meyer, G.A., 1992, Mine tailings sediment contamination in the Soda Butte Creek drainage, Montana and Wyoming: Final report, 16.8-25-92.

_____1993, A polluted flash flood and its consequences: Yellowstone Science, v. 3, no. 1, p. 2-6.

According to National Park Service records, the McLaren tailings impoundment failed in June 1950, spilling a large amount of tailings into the creek. Deposits of the tailings have been found over 15.5 miles downstream, just above the confluence of Soda Butte Creek and the Lamar River.

_____1995, Tailings impoundment failure and floodplain sediment contamination along Soda Butte Creek, Yellowstone National Park, Montana-Wyoming (abs.): Geological Society of America, Abstracts with Programs, v. 27, no. 4, 47 p.

_____1997, Stream ecosystems and geoscience in northeastern Yellowstone National Park (abs): Geological Society of America, Abstracts with Programs, v. 29, no. 6, p. 66.

Meyer, G.A., and Bingham, M.K., 1995, Soda Butte Creek floodplain tailings deposits and McLaren dam-break flood, *in* Meyer, G.A., ed., Late-Pleistocene-Holocene evolution of the northeast Yellowstone landscape: Middlebury, Vt., Middlebury College, Guidebook, Friends of the Pleistocene Rocky Mountain Cell, p. 13-14.

Meyer, G.A., and Watt, P.M., 1998, Mine tailings contamination of floodplain sediments in Yellowstone National Park: National Geographic Society grant #5699-96.

Metals-laden mine waste contaminated the Soda Butte Creek floodplain in Yellowstone National Park when a tailings dam failed in 1950, producing a major flood. A large volume (approximately equal to $3.1x10^4$ *cubic meters) of contaminated sediments was deposited along the 30-km floodplain.*

Miller, W.R., Meier, A.L., and Briggs, P.H., 1997, Geochemical processes and baselines for stream waters for Soda Butte-Lamar Basin and Firehole-Gibbon Basin: U.S. Geological Survey Open-File Report 97-550, 27 p.

There is minimal to no effect on the chemistry of Soda Butte Creek from the presence of mine workings or tailings above Cooke City for this time of year (Fall 1996).

Mills, L.E., and Sharpe, F.P., 1968, Pollution study of Soda Butte Creek, Yellowstone National Park, Wyoming, [unpublished mimeograph]: Fort Collins, Colo., Bureau of Sport Fisheries and Wildlife, Division of Fishery Services unpublished mimeograph, 16 p.

At the request of the National Park Service late in July 1967, and with approval from the Montana Fish and Game Department, a pollution study was initiated on Soda Butte Creek on August 3, 1967. The investigation was to determine if the apparent poor production in the stream is related to possible pollution influences from mining activities near the headwaters and whether or not these influences are of sufficient magnitude to warrant more intensive investigations. Initial investigations were limited to detailed water analyses and determinations of relative abundance of the major orders of aquatic insects inhabiting the substrate at various points along the stream. Detailed water analyses revealed no materials considered toxic to fish or aquatic invertebrates. All samples collected in late summer.

Montana Bureau of Mines and Geology, 1976, Final Report, Acid mine drainage control - feasibility study, Cooke City, Montana: Butte, Mont., Montana Bureau of Mines and Geology, U.S. Environmental Protection Agency grant S-802671, 182 p.

Investigation of the McLaren mine and mill sites, and the Glengary mine area. The McLaren mill site may be characterized by influent stream conditions, low surficial infiltration rates, and poor transmissivity within the tailings. The mill site contributes roughly 77 metric tons of iron per year, which is carried into Yellowstone National Park (3 miles downstream) by Soda Butte Creek. Value of metals within the tailings is about 4.2 million dollars (gold = $2,975,000, silver = $287,400, and copper = $1,006,700). The stability of the tailings pond is questioned because of the appearance of pyrite in the outflow water at a spring. It is proposed that fly ash, a waste product from coal-fueled electric-generation plants with disposal problems of its own, be evaluated for its ability to perform both as a sealant and as an in situ base source to neutralize the acid water resulting from sulfide oxidation.

Montana Department of State Lands, 1986, Application for renewable resource development grant, Soda Butte Creek streambank reclamation project: Helena, Mont., 149 p.

The proposed reclamation plan will relocate Soda Butte Creek back to its original location through the middle of the tailings pile, thus eliminating the seepage of surface water through the tailings. A small drainage ditch will also be constructed along the south side of the tailings to divert surface runoff away from the tailings location. Part of the old Soda Butte Creek channel will be backfilled to act as a dam and divert the creek flows into the proposed diversion. All disturbed areas will be sloped, graded, topsoiled, and revegetated.

Muttkowski, R.A., 1929, The ecology of trout streams in Yellowstone National Park: Roosevelt Wildlife Annals, v. 2, no. 2, p. 155-240.

Work concentrated on Yellowstone and Lamar Rivers and Tower and Lost Creeks, which the author considered to represent the major stream types in the Park.

Nimmo, D. R., Willox, M.J., 1996, Seasonal liabilities from the McLaren tailings on aquatic resources in Soda Butte Creek and Yellowstone National Park, *in* Nelson, J.D., and others, eds., Proceedings of the Third Interagency Conference on Tailings and Mine Waste, Fort Collins, Colorado: Rotterdam, The Netherlands, Balkema Publishing, p. 415-420.

For years, Soda Butte Creek has been adversely affected by metal-laden runoff from the closed McLaren Mine tailings impoundment. In 1993, bioassays were conducted using daphnids, fathead minnows, and amphipods.

Nimmo, D.R., Willox, M.J., LaFrancois, T.D., Chapman, P.L., Brinkman, S.F., and Greene, J.C., 1998, Effects of metal mining and milling on boundary waters of Yellowstone National Park, USA: Environmental Management, v. 22, no. 6, p. 913-926.

Aquatic resources in Soda Butte Creek within Yellowstone National Park, USA, continue to be threatened by heavy metals from historical mining and milling activities that occurred upstream of the park's boundary. This includes the residue of gold, silver, and copper ore mining and processing in the early 1900s near Cooke City, Montana, just downstream of the creek's headwaters. Toxicity tests, using surrogate test species, and analyses of metals in water, sediments, and macroinvertebrate tissue were conducted from 1993 to 1995. Chronic toxicity to test species was greater in the spring than the fall and metal concentrations were elevated in the spring with copper exceeding water quality criteria in 1995. Tests with amphipods using pore water and whole sediment from the creek and copper concentrations in the tissue of macroinvertebrates and fish also suggest that copper is the metal of concern in the watershed. In order to understand current conditions in Soda Butte Creek, heavy metals, especially copper, must be considered important factors in the aquatic and riparian ecosystems within and along the creek extending into Yellowstone National Park.

Norton, D.A., 1993, 1994a, 1995a, 1996a, 1997a, Monitoring of Soda Butte Creek riparian zone: Denver, Colo., U.S. Geological Survey Branch of Geochemistry, Investigator's annual reports, accessed November 26, 1999 at URL http://165.83.23.11/amoeba/resiar.nsf,

Objective [1993, 1994, 1995, 1997 reports]: Establish present-day trace-element concentrations in vegetation, soils, water, and stream sediments of the Soda Butte Creek riparian zone to assess the impact of past mining operations (McLaren Mine) and to monitor the proposed Noranda (Canadian owned) gold, copper, and silver mine to be located 2 miles outside the Park boundary.

Objective [1996 report]: Establish present day trace element concentrations in vegetation, soils, water, and stream sediments of the Soda Butte Creek riparian zone to assess the impact of past mining operations (McLaren Mine) and to provide a chemical baseline for these operations and for the exploratory operations of the Noranda (Canadian owned) gold, copper, and silver mine located 2 miles outside the Park boundary. The baseline is being established in the event that the property trade fails to remove the mining operation. If the trade of lands is successful it will still be necessary to proceed with the study for the clean-up of the historic mine activities on the mountain and of the McLaren tailings and waste ore deposits near Cooke City.

1993, 1994, 1995 Findings and status: Representative vegetation species, stream sediments, and water were collected along the Soda Butte Creek riparian zone, Yellowstone National Park, during a reconnaissance field trip in the fall of 1992. Seven sampling sites were established downstream from the old McLaren Mine tailings site. The McLaren Mine tailings contain elevated concentrations of arsenic, copper, iron, lead, and zinc. Preliminary vegetation results indicate that the highest concentrations of copper, lead, and zinc occur at the tailings sites and decrease downstream in samples of grass, horsetail, and willow. Results for the other species do not reflect this decrease. [1994, 1995]: Iron concentrations in all species sampled do not appear to decrease downstream.

M.A. Chaffee plans to present his findings for a regional geochemical database to the geographic information system for the Greater Yellowstone Area ecosystem at the next annual physical science symposium. We will also present a heavy-metals investigations program sponsored by the Gallatin National Forest where part of it focuses on the Noranda Mine sites.

1996 Findings and status: Monitoring of the Soda Butte Creek watershed has been in progress since 1992, and has been continued to date sampling plant species, soils, water, and stream sediments. Results from the vegetation samples suggest willow and grass will serve as biomonitors. Chemical analysis for plant species has been held up due to lack of funding. Results of water samples taken this past field season have been received by William Miller, and will be reported at the next interagency meeting to be held in the Park during September 1997. These include chemical analysis for cations and anions, pH, conductivity, and alkalinity. Maurice Chaffee will be reporting on our results for stream sediments collected by our team of Survey geologists in September 1996. I have completed a series of pH, conductivity, and temperature measurements of water samples taken in the field and will be reporting on filtration rates and microscopy of precipitate from these samples. At the meeting I will also present my findings on sieve testing of stream sediments and microscopy of the separated fractions with information on their carbonate and iron contents. I plan to organize and moderate the Fourth Interagency Conference on the Soda Butte Creek Watershed to be held in Mammoth in September 1997.

1997 Findings and status: Results on this project were presented at the Forth Interagency Conference held in September, which I organized and moderated. Monitoring of the Soda Butte Creek riparian zone continues to be taking place by a number of agencies presenting papers at the symposium. We have recommended that the gaging station at the park entry on Soda Butte Creek be upgraded for continuous monitoring of the discharge. Our findings on the geochemical sampling and chemical analysis are being accumulated into reports by Maurice Chaffee and associates.

_____1994b, Monitoring of Soda Butte Creek riparian zone (abs. and poster): Proceedings of the American Water Resources Association symposium, Effects of Human-Induced Changes on Hydrologic Systems, Jackson Hole, Wyo., Abstracts and Posters.

_____1995b, Monitoring of Soda Butte Creek riparian zone, (abs. and poster): Proceedings of the American Water Resources Association symposium, Abstracts and Posters.

_____1996b, Monitoring of Soda Butte Creek Riparian Zone, *in* Nelson, J.D., and others, eds., Proceedings of the Third Interagency Conference on Tailings and Mine Waste, Fort Collins, Colorado: Rotterdam, The Netherlands, Balkema Publishing.

A study of cation and anion concentrations in water, and heavy-metal concentrations.

_____1996c, Metal uptake of plants along the Soda Butte Creek watershed in Montana and Wyoming, 1992-1994 (abs. and poster): Second Interagency Conference on Soda Butte Creek Watershed, Yellowstone National Park.

_____1996d, Study of cation and anion concentrations in water, and heavy metal concentrations in stream sediments, along the Soda Butte Creek watershed in Montana and Wyoming, 1992-1994 (abs. and poster): Second Interagency Conference on Soda Butte Creek Watershed, Yellowstone National Park.

_____1997b, Monitoring of Soda Butte Creek Riparian Zone, *in* Nelson, J.D., and others, eds., Proceedings of the Third Interagency Conference on Tailings and Mine Waste, Fort Collins, Colorado: Rotterdam, The Netherlands, Balkema Publishing.

Establish present-day trace-element concentrations in vegetation, soils, water, and stream sediments of the Soda Butte Creek riparian zone to assess the impact of past mining operations (McLaren Mine) and to monitor the proposed Noranda (Canadian owned) gold, copper, and silver mine to be located two miles outside the Park boundary.

_____1997c, Environmental geochemical baseline studies in the Yellowstone National Park area: Proceedings of the Greater Yellowstone Ecosystem Science Conference, Yellowstone National Park.

_____1997d, Dispersion of selected elements in stream sediment samples collected between Cooke City, Montana and the confluence of the Lamar and Yellowstone Rivers: Proceedings of the Third Interagency Conference on Soda Butte Creek Watershed, Yellowstone National Park.

Obermann, W.R., 1998, Estimates of volume and mass for flood-deposited mine tailings along Soda Butte Creek, Yellowstone National Park: Middlebury, Vt., Middlebury College, unpublished Bachelor of Arts thesis, 60 p.

Omang, R.J., U.S. Geological Survey, written commun., 1988, Flood peak and flood routing determinations for Soda Butte Creek: Helena, Mont., Memorandum.

Flood studies conducted by the USGS using channel geometry techniques indicate that for Soda Butte Creek above the Miller Creek confluence the 50-year design flood is 1,040 cubic feet per second (cfs), and the 100-year design flood is 1,430 cubic cfs. Below Miller Creek, the 50-year design flood discharge is 1,200 cfs, and the 100-year design flood discharge is 1,620 cfs. Approximately 700 cfs of the 100-year flood would discharge across the tailings pond. These data clearly indicate the substantial flooding potential which exists at the site.

Omang, R.J., Parrett, Charles, and Hull, J.A., 1983, Flood estimates for ungaged streams in Glacier and Yellowstone National Parks, Montana: U.S. Geological Survey Water-Resources Investigations Report 83-4147, 10 p.

Pickett, F.J., and Chadwick, J.W., 1972, Studies on Soda Butte, Slough, and Iron Springs Creeks, Yellowstone National Park: Bozeman, Mont., Montana State University, Final report for contract 2-101-0387, 54 p.

Seepage from the mill tailings at Cooke City is adversely affecting the water quality of Soda Butte Creek. The natural flora and fauna present above the tailings were either eliminated or severely reduced immediately below the tailings.

Richards, D.C., Marcus, W.A., Nimmo, D.R., 1997, Persistent impacts of mining on macroinvertebrates in Soda Butte Creek: North American Benthological Society.

Satchell, B., 1995, A new battle over Yellowstone Park: U.S. News and World Report, March 13, 1995.

Shands, Tom, 1998,'Smoking gun' - Researchers link old mine tailings to riparian damage: Yellowstone Ecosystem Studies, accessed December 20,1999 at URL *http://fp2.in-tch.com/www.yellowstone.org/p_sodabutte.htm*.

"Our research very clearly shows the impacts of past tailings releases," Dr. Andrew Marcus said, adding the extent of the damage to the Soda Butte drainage extends well within Yellowstone Park. Marcus said that within the grasslands community in the floodplain of Soda Butte, there was decreased biodiversity and decreased biomass. Researchers also compared the macroinvertebrate population of Soda Butte Creek below the McLaren tailings to that of Pebble Creek, which is entirely within the Park, has never been mined, and flows into Soda Butte Creek. In Pebble Creek researchers found 19 different types or organisms. In Soda Butte Creek below the tailings, they only found six types of organisms.

In addition to the plants and insects,,, he (Marcus) said researchers have also found evidence of "bioaccumulation" in fish, particularly the liver and muscle tissue.

Sharpe, F.P., and Arnold, B.B., 1966, Summary report, 1965: Yellowstone National Park, Wyo., Fishery Management Program, Lake and Stream Surveys, 59 p.

Focused on certain streams in the northeast section of the Park. General stream survey intended to classify waters and locate possible problem areas.

Shuler, S., U.S. Forest Service, written commun., 1994: Gardiner, Mont., U.S. Forest Service, Gallatin National Forest, Gardiner Ranger District, unpublished data, 45 p.

In 1993, only two front were found within 300 meters downstream of the McLaren tailings impoundment.

Sonderegger, J.L., 1976, Hydrologic and geochemical controls on tailings pond drainage affecting Soda Butte Creek, Cooke City, Montana (abs.): Geological Society of America, Abstracts with Programs, v. 8, no. 5, p. 634.

Sonderegger, J.L., Wallace, J.J., Jr., and Higgins, G.L., Jr., 1976, Acid mine drainage control – feasibility study, Cooke City, Montana: Butte, Mont., Montana Bureau of Mines and Geology Open-File Report 23, 197 p.

Stoughton, Julie, 1995, The impacts of trace metals on grass communities along the floodplain of Soda Butte Creek: Bozeman, Mont., Montana State University, unpublished Master of Science thesis, 109 p.

Results indicated that the density, diversity and biomass of vegetation decreased at threshold concentrations for metals and pH at 4 meadow sites along Soda Butte Creek. Plant diversity in relation to metals showed a decrease.

Terrasi, J.D., written commun., 1995, Unpublished report on analysis of Soda Butte Creek water and sediments.

U.S. Environmental Protection Agency, 1971a, Baseline water quality survey: Kansas City, Mo., U.S. Environmental Protection Agency, Region VII.

In the vicinity of the McLaren mine tailings on Soda Butte Creek outside of the Park boundary, there is a decrease in the types and numbers of bottom organisms.

_____1971b, Baseline water quality survey report – Yellowstone National Park: Kansas City, Mo., U.S. Environmental Protection Agency, Region VII, 133 p.

_____1972, Yellowstone National Park baseline water quality survey: Denver, Colo., U.S. Environmental Protection Agency, Region VIII report for May – September, 1970, 194 p.

In the vicinity of Cooke City, Montana, a decrease of numbers and types of bottom organisms in Soda Butte Creek indicated marginal water quality.

_____1987, Impact assessment - McLaren mine tailings pile, Cooke City, Montana: Edison, N.J., U.S. Environmental Protection Agency.

Invertebrate densities and diversities decrease immediately below the tailings site and then tend to recover further downstream.

_____1989, Request for removal action approval at the McLaren tailings site, Cooke City, Montana: Action memorandum NPL Site ID #93, 7 p.

A buttress berm was installed by U.S. Environmental Protection Agency and Kennecott to reinforce the tailings dam and some of the tailings below the dam were removed.

U.S. Fish and Wildlife Service, 1977, Fishery and aquatic management program in Yellowstone National Park: Billings, Mont., U.S. Fish and Wildlife Service, Fisheries Resources Technical report for calendar year 1976, 81 p.

While angler use and success were average when compared to other Park fisheries, historical descriptions of Soda Butte Creek suggest fishing is much below its potential. Correction of the stream's pollution problems is needed for any significant improvement in the sport-fishery.

_____1979, Fishery and aquatic management program in Yellowstone National: Billings, Montana., U.S. Fish and Wildlife Service, Fisheries Resources Park Technical report for calendar year 1978, 43 p.

In the late 1800s, Soda Butte Creek had a reputation for "fast fishing and large trout," but by 1931 the fishery was reported as only "fair to poor." Although angler success is presently only slightly above average by Park standards, fishing quality has improved since 1974 despite increasing use, which is unusual. This may indicate that the extensive rehabilitation work done on the McLaren tailings in the late 1960's has had a positive effect on the fish population. Alternatively, it may suggest that there is a population interaction with the Lamar River which has been catch-and-release only fishing for six years and has built up a robust population.

_____1981, Fishery and aquatic management program in Yellowstone National Park: Billings, Mont., U.S. Fish and Wildlife Service, Fisheries Resources Park Technical report for calendar year 1980, 23 p.

Declines in the Soda Butte fishery have been compounded by pollution from mine tailings at an abandoned mine site in Cooke City, Montana. Angler use on this stream was high in the early 1970's, fell in 1974-75, and has increased since that time. Measures of success continue to be above average for Park waters; however, these rates are believed to be artificially supported by population interaction with the Lamar River which has a documented increase in robustness since catch-and-release regulations were implemented in 1974.

_____1985, Fishery and aquatic management program in Yellowstone National Park: Billings, Mont., U.S. Fish and Wildlife Service, Fisheries Resources Park Technical report for calendar year 1984.

Soda Butte Creek contains the ninth most popular stream fishery in YNP. Approximately 80 percent of the fish landed in Soda Butte Creek are released. A decrease in angler use has been the most obvious change in the Soda Butte fishery since it was last surveyed in 1981. An increase in fish numbers in the upper section signifies improving conditions for the trout population.

_____1992, 1993: Recovery of a cutthroat trout population in a 5-kilometer reach of Soda Butte Creek: Mammoth, Wyo., U.S. Fish and Wildlife Service, Yellowstone National Park, Investigator's annual reports, accessed November 24,1999 at URL http://165.83.23.11/amoeba/resiar.nsf,

Objective: To monitor the recovery of the cutthroat trout population affected by the fish toxin rotenone during fish management activities in 1988.

1992, 1993 Findings and status: Abundance, community length structure, and age distribution are similar to pretreatment levels, indicating recovery of population.

Varley, John, 1992, 1993, 1994, Soda Butte Creek mine tailings analysis: Mammoth, Wyo., National Park Service, Yellowstone National Park Center for Resources, Investigator's annual reports, accessed November 24,1999 at URL http://165.83.23.11/amoeba/resiar.nsf,

Objective: In 1991, sediments were discovered along the entire length of Soda Butte Creek that have been identified as tailings from the McLaren tailings site above Cooke City. Toxicity and heavy metals analysis will be performed to determine the impact of these tailings on the ecology of the area.

1992-94 Findings and status: None.

Weight, Willis, 1998, Groundwater-flow assessment of the upper Soda Butte Creek drainage basin, Park County, Montana and Wyoming: Butte, Mont., University of Montana, Investigator's annual report, accessed November 24,1999 at URL http://165.83.23.11/amoeba/resiar.nsf,

Objective: To understand the basic hydrogeology of the upper Soda Butte drainage from Silver Gate to Cooke City. Characterization will be performed through performing pumping tests, static water-level surveys, and stream gaging. Additional analysis of the role of bedrock is to be explored. The data will be integrated into a groundwater flow model.

Findings and Status: Three aquifer tests were performed and water level surveys were conducted in the summer and fall of 1997 and throughout the fall of 1998. Stream gaging was performed. A groundwater flow model using a graphical interface GMS was used to create a three layer model of the area. This was put together as part of a MS thesis by Amy Huskey. She defended her thesis is 1998, but corrections are still underway. Alan English is continuing a thesis study in the Silver Gate area, including water-quality data.

Womack, Ray, geological consultant, written commun., 1984, Probable maximum flood and failure hazard, McLaren mill tailings, Cooke City, Montana: Billings, Mont.

Probable maximum flood is approximately 14,000 cubic feet per second (cfs), but would likely range from 11,000 to 18,000 cfs. In the event of a probable maximum flood the McLaren tailings impoundment is likely to fail, releasing large amounts of tailings downstream.

Wright, A., 1998, The use of multispectral digital imager to map hydrogeomorphic stream units in Soda Butte and Cache Creeks, Montana and Wyoming: Bozeman, Mont., Montana State University, unpublished Master of Science thesis, 76 p.

APPENDIX B

FIELD PARAMETERS AND DISSOLVED SULFATE CONCENTRATIONS IN SYNOPTIC SAMPLES FROM SODA BUTTE CREEK AND INFLOWS, MONTANA AND WYOMING, AUGUST 20, 1999

Appendix B. *Field parameters and dissolved sulfate concentrations in synoptic samples from Soda Butte Creek and inflows, Montana and Wyoming, August 20, 1999*

[Distance, distance downstream from injection site, in meters; Temperature, water temperature measured onsite, in degrees Celsius; pH, in standard units; Ksc, specific conductance, in microsiemens per centimeter at 25 degrees Celsius; Sulfate, concentrations in milligrams per liter; LB, left bank; RB, right bank]

Distance	Site description	Tempera-ture	pH	Ksc	Sulfate
	Sampling sites on Soda Butte Creek				
-10	T0 Site--Upstream from injection	5.5	7.9	225	5.64
35	First synoptic-sample site	5.0	8.1	242	5.60
85	Site to check mixing	5.0	8.1	243	5.62
133	Above first drainage from mill site	5.0	8.1	244	5.70
168	Near bedrock outcrop	7.5	8.3	242	5.64
232	T1 Site--upstream from McLaren Tailings	7.5	8.4	243	5.40
322	Above road crossing at tailings; "driving range"	8.0	8.4	243	5.74
372	Riffle below Mill site	8.5	8.2	242	5.77
445	Above RB inflow that comes through pipe	8.5	8.4	243	5.63
505	Below cobble inflow	8.5	8.4	239	6.49
565	Above LB white precipitate--A	8.0	8.4	242	7.65
565	Above LB white precipitate--B	8.0	8.1	242	7.91
642	To separate metal-rich inflows	7.5	8.0	266	18.4
698	At log above largest flowing inflow	6.5	8.2	266	20.4
760	At stump near narrow bend	6.5	8.1	285	29.6
820	Above Miller Creek	8.5	8.0	288	31.3
940	Below Miller Creek	6.5	8.2	263	29.0
1028	Below Cooke City inflow	6.0	8.2	262	30.0
1148	Below Soda Butte Lodge	6.0	8.2	261	29.2
1323	Near LB cabin with green roofing	6.0	8.2	261	29.6
1529	Near path from Cooke City	5.5	8.2	260	29.6
1679	T2 Site--Above Republic Street culvert	5.5	8.2	260	28.2
1785	Above Republic Creek	12.0	8.4	266	29.6
1922	Below Republic Creek	12.5	8.2	111	4.73
2172	Above braided channel	13.0	8.3	111	4.70
2422	Above oxbow	13.5	8.2	111	4.94
2692	Below RB inflow	12.0	7.9	123	5.46
2858	Above RB inflow	12.0	8.1	132	6.35
3052	Channel narrows	11.5	8.3	140	6.54
3190	Above LB inflow	8.0	8.3	140	6.40
3490	At meadow, above Sheep Creek	14.0	8.3	144	6.87
3720	Below Sheep Creek	13.0	8.4	144	6.44
4020	View to Sheep Creek drainage	12.5	8.4	149	6.58
4420	Below braids and RB inflow	13.0	8.3	156	7.01
4720	Below bend with first LB homes	12.5	8.4	157	7.07
5136	Near RB campfire & cabin	12.0	8.3	159	7.89
5910	T3 site--Below canyon inflow	12.0	8.6	157	7.27
6086	At railroad car bridge (private)	11.0	8.2	157	6.95
6395	Upstream end of town of Silver Gate	1.5	8.3	158	7.02
6757	Above log jam at bend	11.5	8.4	159	6.98
7107	Above Silver Gate Bridge	12.0	8.3	160	7.36
7425	Below second bridge	12.0	8.4	163	6.98

Appendix B. *Field parameters and dissolved sulfate concentrations in synoptic samples from Soda Butte Creek and inflows, Montana and Wyoming, August 20, 1999--Continued*

Distance	Site description	Tempera-ture	pH	Ksc	Sulfate
	Sampling sites on Soda Butte Creek--Continued				
7745	At bend near highway 22	13.0	8.6	164	7.28
8090	Above LB talus cone	13.5	8.5	166	7.43
8247	above low conductance inflow	10.5	8.6	167	7.33
8379	At double tree fall across stream	12.5	8.6	149	6.09
8501	T4 site--At Yellowstone National Park boundary	13.5	8.6	149	6.29
	Inflow sampling sites				
146	LB inflow from pit	6.0	8.0	243	6.23
195	RB inflow from pit	7.0	7.6	237	7.90
455	RB inflow through cobbles	13.5	8.3	161	22.3
569	LB inflow from pit at base of bank	9.0	4.0	472	279
605	Pit at small pipe LB	7.0	5.4	1552	2,450
607	Pit at base of stream bank LB	10.0	4.2	1536	2,550
619	Pit at base of tree roots LB	8.5	6.6	1009	468
620	RB series of small inflows	5.0	7.8	368	65.0
643	Small iron bog about 10 meters from stream LB	9.0	6.6	551	217
683	Water seeping from stream bank LB	8.0	7.7	512	93.7
710	Large flowing LB inflow from toe of tailings	8.0	7.0	741	272
825	Miller Creek inflow RB	8.5	8.1	160	22.1
970	Clear water from Cooke City	5.5	7.9	255	31.7
1037	Second city inflow	5.5	7.7	219	25.6
1859	Republic Creek inflow LB	12.0	8.3	87	1.58
2572	RB inflow at edge of cobbles near bank	11.0	8.6	345	10.2
2792	LB drainage from willows	8.5	7.9	253	17.9
2885	RB inflow sample back upstream	12.0	8.5	299	8.16
3204	LB inflow drains back away from stream	8.0	8.4	227	7.69
3623	Sheep Creek RB	10.5	8.4	135	4.37
4110	RB inflow draining large cobble bars	6.5	8.0	187	3.43
4886	RB inflow at large, grey home	7.0	8.4	242	19.4
5171	LB inflow from willow marsh	10.5	8.5	202	11.5
5568	Wyoming Creek LB	10.5	8.3	59	1.75
6419	RB inflow near small cabin	8.5	8.1	240	8.87
8117	LB inflow from large Guitar Lake canyon	12.5	7.2	66	0.75
8267	Unnamed Tributary LB	10.5	8.2	41	0.75
8387	Silver Creek RB	16.5	8.7	174	3.95

APPENDIX C

DISSOLVED AND TOTAL-RECOVERABLE CONSTITUENT CONCENTRATIONS IN SYNOPTIC SAMPLES FROM SODA BUTTE CREEK AND INFLOWS, MONTANA AND WYOMING, AUGUST 20, 1999

Appendix C. *Dissolved and total-recoverable constituent concentrations in synoptic samples from Soda Butte Creek and inflows, Montana and Wyoming, August 20, 1999*

[All concentrations in milligrams per liter; Distance, distance downstream from injection site, in meters; µm, micrometer]

Distance	Alumi-num	Arsenic	Calcium	Cadmium	Copper	Iron	Potas-sium	Magne-sium	Manga-nese	Sodium	Nickel	Lead	Silica	Stron-tium	Zinc
Soda Butte Creek, dissolved (0.45 µm filter) concentrations															
-10	0.026	<0.002	35.0	<0.008	<0.010	0.025	0.622	6.59	<0.003	1.13	<0.040	<0.100	11.9	0.105	0.037
35	<.010	<.002	36.8	<.008	<.010	<.010	.607	6.53	<.003	1.10	<.040	<.100	10.3	.104	<.020
85	<.010	<.002	37.3	<.008	<.010	<.010	.603	6.60	<.003	1.10	<.040	<.100	10.3	.105	<.020
133	<.010	<.002	37.6	<.008	<.010	<.010	.594	6.63	<.003	1.12	<.040	<.100	10.4	.104	<.020
168	<.010	<.002	36.7	<.008	<.010	<.010	.613	6.49	<.003	1.13	<.040	<.100	10.2	.104	<.020
232	<.010	<.002	37.1	<.008	<.010	<.010	.617	6.53	<.003	1.12	<.040	<.100	10.4	.106	<.020
322	<.010	<.002	37.2	<.008	<.010	<.010	.613	6.56	<.003	1.10	<.040	<.100	10.3	.104	<.020
372	.011	<.002	37.6	<.008	<.010	<.010	.623	6.69	<.003	1.12	<.040	<.100	10.4	.106	<.020
445	<.010	<.002	37.8	<.008	<.010	<.010	.611	6.66	<.003	1.10	<.040	<.100	10.5	.105	<.020
505	<.010	<.002	36.3	<.008	<.010	<.010	.618	6.38	<.003	1.09	<.040	<.100	10.1	.103	<.020
642	<.010	<.002	4.1	<.008	<.010	.106	.660	7.08	.024	1.12	<.040	<.100	10.2	.108	<.020
698	.038	<.002	38.1	<.008	<.010	.118	.673	7.21	.031	1.13	<.040	<.100	11.9	.108	.020
760	<.010	<.002	44.5	<.008	<.010	.013	.770	7.90	.060	1.14	<.040	<.100	10.3	.112	<.020
820	<.010	<.002	44.2	<.008	<.010	.061	.792	7.91	.055	1.17	<.040	<.100	9.94	.113	<.020
940	.017	<.002	41.1	<.008	<.010	.062	.716	7.16	.037	1.05	<.040	<.100	9.77	.105	<.020
1,028	<.010	<.002	4.8	<.008	<.010	.098	.724	7.08	.036	1.06	<.040	<.100	9.85	.106	<.020
1,148	<.010	<.002	4.8	<.008	<.010	.045	.712	7.05	.035	1.05	<.040	<.100	9.81	.105	<.020
1,323	<.010	<.002	41.6	<.008	<.010	.072	.735	7.11	.020	.985	<.040	<.100	10.1	.104	<.020
1,785	<.010	<.002	42.5	<.008	<.010	.096	.799	7.26	.014	1.02	<.040	<.100	10.5	.106	<.020
2,422	.163	<.002	13.5	<.008	<.010	.329	.421	3.57	<.003	4.79	<.040	<.100	17.4	.054	<.020
2,692	.034	.011	15.3	<.008	<.010	.070	.404	3.72	<.003	4.60	<.040	<.100	15.6	.058	<.020
2,858	.065	.004	16.0	<.008	<.010	.083	.431	4.02	<.003	4.55	<.040	<.100	16.2	.064	<.020
3,052	.062	<.002	17.1	<.008	<.010	.082	.458	4.32	<.003	4.40	<.040	<.100	16.2	.068	<.020
3,190	.060	<.002	17.1	<.008	<.010	.073	.456	4.38	<.003	4.46	<.040	<.100	15.9	.067	.023
3,490	.035	.004	19.3	<.008	<.010	.061	.460	4.54	<.003	4.42	<.040	<.100	15.2	.069	<.020
3,720	<.010	<.002	19.3	<.008	<.010	.044	.422	4.76	<.003	3.57	<.040	<.100	12.8	.074	<.020

Appendix C. *Dissolved and total-recoverable constituent concentrations in synoptic samples from Soda Butte Creek and inflows, Montana and Wyoming, August 20, 1999--Continued*

Distance	Alumi-num	Arsenic	Calcium	Cadmium	Copper	Iron	Potas-sium	Magne-sium	Manga-nese	Sodium	Nickel	Lead	Silica	Stron-tium	Zinc
Soda Butte Creek, dissolved (0.45 µm filter) concentrations--Continued															
4,020	0.019	<0.002	2.4	<0.008	<0.010	0.039	0.450	5.00	<0.003	3.66	<.040	<0.100	13.4	0.077	<0.020
4,420	.024	<.002	21.4	<.008	<.010	.021	.426	5.06	<.003	3.40	<.040	<.100	12.4	.081	<.020
4,720	.024	.002	22.2	<.008	<.010	.042	.471	5.12	<.003	3.57	<.040	<.100	13.2	.082	<.020
5,136	.012	<.002	22.5	<.008	<.010	.018	.442	5.39	<.003	3.28	<.040	<.100	12.2	.085	<.020
5,910	<.010	<.002	21.2	<.008	<.010	.025	.448	5.10	<.003	3.46	<.040	<.100	12.4	.083	<.020
6,086	.017	<.002	21.4	<.008	<.010	.030	.476	5.15	<.003	3.60	<.040	<.100	13.1	.082	<.020
6,395	.046	.005	20.2	<.008	<.010	.041	.476	5.11	<.003	3.76	<.040	<.100	13.6	.084	<.020
6,757	.039	<.002	20.5	<.008	<.010	.040	.494	5.16	<.003	3.84	<.040	<.100	13.6	.086	.023
7,107	.042	<.002	20.7	<.008	<.010	.039	.494	5.16	<.003	3.85	<.040	<.100	13.6	.086	.021
7,425	.017	.008	22.8	<.008	<.010	.026	.497	5.36	<.003	3.70	<.040	<.100	13.2	.088	<.020
7,745	.012	.008	22.6	<.008	<.010	.028	.491	5.30	<.003	3.69	<.040	<.100	13.0	.088	<.020
8,090	.021	.004	23.2	<.008	<.010	.027	.499	5.41	<.003	3.81	<.040	<.100	13.3	.090	<.020
8,247	.048	.002	21.8	<.008	<.010	.045	.523	5.35	<.003	4.06	<.040	<.100	13.7	.093	.024
8,379	.066	.009	18.8	<.008	<.010	.071	.506	4.93	<.003	4.26	<.040	<.100	14.8	.080	<.020
8,501	.032	.004	20.2	<.008	<.010	.058	.484	4.96	<.003	4.07	<.040	<.100	14.0	.078	<.020
Soda Butte Creek, total-recoverable concentrations															
-10	<.028	<.002	36.5	<.010	<.012	<.014	.611	6.68	<.003	1.16	<.050	<.130	10.4	.105	<.040
35	<.028	<.002	36.2	<.010	<.012	<.014	.610	6.63	<.003	1.13	<.050	<.130	10.4	.104	<.040
85	<.028	<.002	36.2	<.010	<.012	<.014	.604	6.61	<.003	1.13	<.050	<.130	10.8	.102	<.040
133	<.028	.003	36.6	<.010	<.012	<.014	.615	6.64	<.003	1.12	<.050	<.130	10.5	.104	<.040
168	<.028	<.002	36.5	<.010	<.012	<.014	.630	6.66	<.003	1.18	<.050	<.130	10.7	.106	<.040
232	.035	.009	36.4	<.010	<.012	.033	.671	6.67	<.003	1.15	<.050	<.130	10.9	.106	<.040
322	.042	<.002	37.0	<.010	<.012	.041	.676	6.76	<.003	1.13	<.050	<.130	10.8	.106	<.040
372	<.028	<.002	40.3	<.010	<.012	.035	.726	7.36	<.003	1.24	<.050	<.130	11.8	.116	<.040
445	.035	<.002	37.1	<.010	<.012	.039	.675	6.80	<.003	1.17	<.050	<.130	10.9	.107	<.040
505	.049	<.002	35.9	<.010	<.012	.053	.665	6.52	<.003	1.09	<.050	<.130	10.8	.105	<.040
565A	<.028	.010	36.3	<.010	<.012	.009	.630	6.56	<.003	1.13	<.050	<.130	10.6	.105	<.040
565B	.047	<.002	36.3	<.010	<.012	.054	.666	6.60	<.003	1.10	<.050	<.130	10.6	.104	<.040

Appendix C. *Dissolved and total-recoverable constituent concentrations in synoptic samples from Soda Butte Creek and inflows, Montana and Wyoming, August 20, 1999--Continued*

Distance	Alumi-num	Arsenic	Calcium	Cadmium	Copper	Iron	Potas-sium	Magne-sium	Manga-nese	Sodium	Nickel	Lead	Silica	Stron-tium	Zinc
Soda Butte Creek, total-recoverable concentrations-Continued															
642	0.049	0.005	39.4	<0.010	<0.012	0.552	0.711	7.15	0.037	1.11	<0.050	<0.130	10.7	0.107	<0.040
698	.061	<.002	40.0	<.010	<.012	.539	.719	7.28	.038	1.11	<.050	<.130	10.8	.108	<.040
760	<.028	.008	43.1	<.010	<.012	1.24	.783	7.98	.063	1.16	<.050	<.130	10.6	.111	<.040
820	.051	.006	43.7	<.010	<.012	1.30	.827	8.09	.064	1.15	<.050	<.130	10.9	.112	<.040
940	.045	<.002	40.0	<.010	<.012	.746	.777	7.17	.049	1.05	<.050	<.130	10.3	.105	<.040
1,028	<.028	<.002	40.4	<.010	<.012	.904	.728	7.23	.041	1.08	<.050	<.130	10.4	.107	<.040
1,148	<.028	<.002	40.6	<.010	<.012	.833	.732	7.19	.038	1.07	<.050	<.130	10.3	.105	<.040
1,323	.047	<.002	40.0	<.010	<.012	.631	.770	7.10	.045	1.04	<.050	<.130	10.2	.104	<.040
1,529	<.028	<.002	40.1	<.010	<.012	.724	.734	7.02	.035	1.05	<.050	<.130	10.1	.104	<.040
1,679	.043	.008	39.9	<.010	<.012	.581	.771	7.10	.043	1.06	<.050	<.130	10.4	.106	<.040
1,785	<.028	.005	40.7	<.010	<.012	.640	.784	7.19	.032	1.07	<.050	<.130	10.4	.106	<.040
1,922	.380	<.002	13.3	<.010	<.012	.824	.451	3.89	<.003	4.87	<.050	<.130	19.5	.056	<.040
2,172	.518	<.002	13.4	<.010	<.012	.915	.476	3.96	<.003	4.90	<.050	<.130	20.4	.057	.044
2,422	.392	.002	13.3	<.010	<.012	.809	.448	3.89	<.003	4.82	<.050	<.130	19.4	.055	<.040
2,692	.340	<.002	15.3	<.010	<.012	.737	.444	4.26	<.003	4.74	<.050	<.130	18.8	.061	<.040
2,858	.320	<.002	16.9	<.010	<.012	.690	.466	4.47	<.003	4.62	<.050	<.130	18.3	.065	<.040
3,052	.323	.004	17.2	<.010	<.012	.551	.507	4.81	<.003	4.49	<.050	<.130	18.9	.067	<.040
3,190	.277	<.002	17.2	<.010	<.012	.530	.506	4.79	<.003	4.47	<.050	<.130	18.4	.067	<.040
3,490	.271	<.002	18.9	<.010	<.012	.598	.500	4.92	<.003	4.45	<.050	<.130	18.0	.071	<.040
3,720	.211	.007	18.9	<.010	<.012	.440	.453	5.15	<.003	3.82	<.050	<.130	15.4	.075	<.040
4,020	.196	.004	19.9	<.010	<.012	.395	.457	5.10	<.003	3.71	<.050	<.130	15.1	.078	<.040
4,420	.180	.008	21.4	<.010	<.012	.343	.522	5.36	.005	3.51	<.050	<.130	15.2	.083	<.040
4,720	.182	.010	21.3	<.010	<.012	.326	.529	5.33	.003	3.51	<.050	<.130	15.1	.083	<.040
5,136	.153	<.002	22.3	<.010	<.012	.300	.528	5.73	.003	3.43	<.050	<.130	14.6	.087	<.040
5,910	.193	.002	21.3	<.010	<.012	.349	.533	5.51	.004	3.60	<.050	<.130	14.9	.084	<.040
6,086	.192	<.002	21.2	<.010	<.012	.375	.502	5.46	<.003	3.69	<.050	<.130	14.8	.084	<.040
6,395	.201	<.002	21.3	<.010	<.012	.359	.502	5.44	<.003	3.68	<.050	<.130	14.8	.085	<.040
6,757	.210	.008	20.7	<.010	<.012	.327	.528	5.42	<.003	3.89	<.050	<.130	15.5	.087	<.040

Appendix C. *Dissolved and total-recoverable constituent concentrations in synoptic samples from Soda Butte Creek and inflows, Montana and Wyoming, August 20, 1999--Continued*

Distance	Alumi-num	Arsenic	Calcium	Cadmium	Copper	Iron	Potas-sium	Magne-sium	Manga-nese	Sodium	Nickel	Lead	Silica	Stron-tium	Zinc
Soda Butte Creek, total-recoverable concentrations--Continued															
7,107	0.198	<0.002	20.8	<0.010	<0.012	.308	0.529	5.40	<0.003	3.84	<0.050	<0.130	15.3	0.086	<0.040
7,425	.294	<.002	21.3	<.010	<.012	.381	.562	5.52	<.003	4.02	<.050	<.130	16.5	.091	<.040
7,745	.207	<.002	21.2	<.010	<.012	.299	.535	5.44	<.003	3.94	<.050	<.130	14.7	.089	<.040
8,090	.172	.002	21.5	<.010	<.012	.281	.534	5.49	<.003	4.05	<.050	<.130	15.4	.092	<.040
8,247	.206	<.002	21.8	<.010	<.012	.302	.550	5.57	<.003	4.05	<.050	<.130	15.5	.092	<.040
8,379	.368	<.002	19.0	<.010	<.012	.506	.559	5.09	<.003	4.28	<.050	<.130	17.7	.080	<.040
8,501	.252	<.002	19.9	<.010	<.012	.517	.526	5.11	<.003	4.09	<.050	<.130	16.2	.081	<.040
Inflows, dissolved (0.45 μm filter) concentrations															
146	.089	<.002	34.9	<.008	<.010	.109	.725	6.63	<.003	1.19	<.040	<.100	11.8	.107	<.020
195	<.010	<.002	38.2	<.008	<.010	.025	.666	6.26	<.003	1.08	<.040	<.100	12.6	.097	<.020
455	<.010	<.002	26.3	<.008	<.010	<.010	.553	3.69	<.003	.795	<.040	<.100	8.63	.077	<.020
569	8.96	<.002	49.4	<.008	1.90	2.10	1.56	14.4	1.59	1.71	.047	<.100	47.0	.116	.245
605	.603	<.002	273	.008	.127	7.33	3.22	55.3	8.26	3.06	.163	<.100	25.1	.434	.413
607	2.47	<.002	232	.008	.149	5.3	3.90	56.2	5.29	2.91	.114	<.100	30.3	.376	.377
619	.482	<.002	153	<.008	<.010	56.1	5.92	29.5	1.62	1.85	<.040	<.100	22.1	.223	.030
620	<.010	<.002	60.3	<.008	<.010	<.010	.769	9.81	<.003	1.22	<.040	<.100	11.1	.134	<.020
643	<.010	<.002	59.2	<.008	<.010	11.9	3.06	14.7	1.85	1.35	<.040	<.100	13.0	.104	<.020
683	<.010	<.002	85.3	<.008	<.010	.057	1.04	15.4	.157	1.54	<.040	<.100	13.0	.168	<.020
710	<.010	<.002	114	<.008	<.010	15.2	3.97	25.5	1.08	1.83	<.040	<.100	13.0	.211	<.020
825	<.010	<.002	26.3	<.008	<.010	<.010	.519	3.70	<.003	.773	<.040	<.100	8.50	.078	<.020
970	<.010	<.002	43.8	<.008	<.010	<.010	.730	5.86	<.003	.970	<.040	<.100	9.65	.103	<.020
1,037	<.010	<.002	37.4	<.008	<.010	<.010	.689	4.94	<.003	.942	<.040	<.100	9.40	.089	<.020
1,859	.083	<.002	8.74	<.008	<.010	.129	.363	2.85	<.003	5.41	<.040	<.100	18.0	.047	.025
2,572	.034	<.002	49.5	<.008	<.010	.020	.876	14.6	<.003	1.21	<.040	<.100	12.2	.193	<.020
2,792	.120	.017	34.3	<.008	.036	.138	1.44	6.89	.020	4.30	<.040	<.100	14.4	.116	<.020
2,885	.037	<.002	38.0	<.008	<.010	.027	.902	15.4	<.003	1.20	<.040	<.100	11.0	.176	.091
3,204	<.010	.010	31.8	<.008	<.010	<.010	.569	8.84	<.003	3.32	<.040	<.100	10.4	.227	<.020
3,623	<.010	<.002	18.6	<.008	<.010	<.010	.306	5.43	<.003	1.74	<.040	<.100	7.95	.082	<.020

Appendix C. *Dissolved and total-recoverable constituent concentrations in synoptic samples from Soda Butte Creek and inflows, Montana and Wyoming, August 20, 1999--Continued*

Distance	Alumi-num	Arsenic	Calcium	Cadmium	Copper	Iron	Potas-sium	Magne-sium	Manga-nese	Sodium	Nickel	Lead	Silica	Stron-tium	Zinc
Inflows, dissolved (0.45 μm filter) concentrations--Continued															
4,110	<0.010	<0.002	28.0	<0.008	<0.010	<0.010	0.432	5.99	<0.003	1.66	<0.040	<0.100	9.39	0.092	<0.020
4,886	.024	<.002	29.0	<.008	<.010	.019	.616	11.8	<.003	1.48	<.040	<0100	8.14	.146	<.020
5,171	<.010	<.002	28.9	<.008	<.010	<.010	.504	6.01	<.003	4.08	<.040	<.100	12.6	.137	<.020
5,568	.180	<.002	4.65	<.008	<.010	.368	.315	1.73	<.003	6.43	<.040	<.100	19.0	.036	<.020
6,419	.019	.009	32.3	<.008	<.010	.019	1.22	9.02	<.003	6.25	<.040	<.100	8.63	.226	<.020
8,117	.636	.003	5.56	<.008	<.010	1.56	.505	3.22	<.003	5.98	<.040	<.100	31.0	.021	<.020
8,267	.188	<.002	2.23	<.008	<.010	.456	.362	1.33	<.003	5.55	<.040	<.100	20.0	.009	<.020
8,387	.010	.007	21.8	<.008	<.010	.011	.582	5.53	<.003	7.64	<.040	<.100	14.0	.092	<.020
Inflows, total-recoverable concentrations															
146	6.52	<.002	41.9	<.010	.074	9.10	1.87	9.01	.435	1.71	<.050	<.130	40.5	.134	.091
195	6.09	<.002	39.7	.012	.291	55.3	4.85	8.95	.127	1.97	<.050	<.130	58.6	.150	.062
455	.032	.013	25.6	<.010	<.012	0.027	.616	3.70	<.003	.753	<.050	<.130	8.91	.078	<.040
569	122	<.002	52.8	.063	6.08	418	4.86	27.1	2.60	2.81	.200	.603	187	.185	.772
605	9.54	<.002	279	.016	.558	45.4	4.30	59.7	7.74	3.82	.178	<.130	59.9	.463	.463
607	6.52	<.002	234	.015	.255	71.5	4.54	59.1	5.03	3.36	.116	<.130	48.2	.379	.336
619	.926	<.002	150	.010	.021	60.0	5.99	29.7	1.62	1.83	<.050	<.130	25.9	.221	<.040
620	<.028	<.002	60.8	<.010	<.012	<.014	.788	10.2	<.003	1.25	<.050	<.130	11.3	.134	<.040
643	1.46	<.002	72.8	<.010	.086	31.6	3.86	18.7	2.35	1.66	<.050	<.130	19.7	.130	<.040
683	.149	<.002	86.4	<.010	<.012	2.62	1.08	16.0	.156	1.60	<.050	<.130	14.1	.169	<.040
710	.032	<.002	113	<.010	<.012	24.0	3.94	25.4	1.08	1.78	<.050	<.130	14.5	.210	<.040
825	<.028	<.002	25.6	<.010	<.012	<.014	.531	3.71	<.003	.748	<.050	<.130	8.57	.078	<.040
970	<.028	.004	43.2	<.010	<.012	<.014	.745	6.00	<.003	1.02	<.050	<.130	9.96	.104	<.040
1,037	<.028	<.002	37.1	<.010	<.012	<.014	.712	5.07	<.003	.998	<.050	<.130	9.68	.090	<.040
1,859	.451	<.002	9.41	<.010	<.012	.885	.421	3.41	<.003	5.49	<.050	<.130	21.1	.049	<.040
2,572	.069	<.002	52.3	<.010	<.012	.035	.897	14.7	<.003	1.22	<.050	<.130	11.2	.193	<.040
2,792	<.028	.006	38.5	<.010	<.012	<.014	.667	6.97	<.003	4.08	<.050	<.130	14.1	.114	<.040
2,885	.063	<.002	37.6	<.010	<.012	.048	.895	15.1	<.003	1.17	<.050	<.130	10.2	.168	<.040

Appendix C. *Dissolved and total-recoverable constituent concentrations in synoptic samples from Soda Butte Creek and inflows, Montana and Wyoming, August 20, 1999--Continued*

Distance	Alumi-num	Arsenic	Calcium	Cadmium	Copper	Iron	Potas-sium	Magne-sium	Manga-nese	Sodium	Nickel	Lead	Silica	Stron-tium	Zinc
Inflows, total-recoverable concentrations--Continued															
3,204	<0.028	0.005	31.1	<0.010	<0.012	<0.014	0.553	8.91	<0.003	3.36	<0.050	<0.130	10.2	0.230	<0.040
3,623	.035	<.002	17.2	<.010	<.012	.033	.331	5.36	<.003	1.90	<.050	<.130	8.25	.081	<.040
4,110	.036	<.002	26.7	<.010	<.012	.023	.476	6.04	<.003	1.76	<.050	<.130	10.0	.091	<.040
4,886	<.028	<.002	29.3	<.010	<.012	.027	.592	11.8	<.003	1.51	<.050	<.130	7.62	.145	<.040
5,171	.042	.003	28.8	<.010	<.012	.050	.523	6.18	<.003	4.11	<.050	<.130	13.3	.139	<.040
5,568	.642	<.002	4.94	<.010	<.012	1.44	.501	2.58	.011	6.57	<.050	<.130	26.3	.040	<.040
6,419	.964	<.002	31.8	<.010	<.012	.915	1.40	9.41	.004	6.31	<.050	<.130	14.5	.234	<.040
8,117	.890	<.002	5.83	<.010	<.012	1.86	.521	3.42	<.003	5.98	<.050	<.130	30.5	.021	<.040
8,267	.862	<.002	2.53	<.010	<.012	1.58	.460	2.17	<.003	5.55	<.050	<.130	26.2	.012	<.040
8,387	.101	<.002	20.3	<.010	<.012	.087	.592	5.47	<.003	7.69	<.050	<.130	14.2	.091	<.040

USGS

APPENDIX D

ANALYSIS OF WATER SAMPLES COLLECTED AT U.S. GEOLOGICAL SURVEY GAGING STATION 06187915, WATER YEAR 1999

Appendix D. *Analysis of water samples collected at U.S. Geological Survey gaging station 06187915, water year 1999*

(Modified from Swanson and others, 2000, p. 424-426)

[All units as milligrams per liter unless otherwise indicated; ft^3/s, cubic feet per second; µS/cm, microsiemens per centimeter at 25 degrees Celsius; ^{O}C, degrees Celsius; mm of Hg, millimeters of mercury; --, missing data; <, less than minimum reporting level; E, estimated]

Date	Time	Discharge (ft^3/s)	Specific conductance (µS/cm)	pH (standard units)	Air temperature (^{O}C)	Water temperature (^{O}C)	Barometric pressure (mm of Hg)	Oxygen, dissolved	Oxygen, dissolved (percent)	Hardness, total (mg/L as $CaCO_3$)	Calcium, total recoverable	Calcium, dissolved
01-21-	1000	2.0	238	7.7	-3.0	0.0	570	12.0	110	120	34	34
02-09-	1400	2.6	240	7.7	.5	.5	569	11.1	103	120	34	34
03-03-	1400	1.8	266	7.7	.0	.0	579	12.2	110	110	33	32
04-05-	1500	2.4	236	8.3	.0	2.0	572	11.3	109	110	33.9	33
05-14-	1100	E20	219	8.3	3.5	4.0	580	10.4	105	110	31.7	30
05-25-	1215	213	121	8.1	21.0	6.0	583	8.6	91	54	16.8	16
06-08-	1330	261	130	7.8	3.0	5.0	576	10.1	105	60	16.9	18
06-22-	0800	545	81	7.9	10.0	3.5	574	10.5	105	34	15.8	10
07-13-	1530	294	81	7.7	30.0	10.5	580	10.8	128	33	9.6	9.6
08-10-	0800	45	140	8.1	17.0	6.0	582	12.4	130	64	18.4	19
09-13-	0930	19	180	8.1	6.0	1.5	585	10.4	96	79	23.3	23

Date	Magnesium, total recoverable	Magnesium, dissolved	Sodium, total recoverable	Sodium, dissolved	Sodium adsorption ratio	Potassium, total recoverable	Potassium dissolved	Bicarbonate, field (as HCO_3)	Alkalinity, dissolved, field (as $CaCO_3$)	Alkalinity, dissolved, lab (as $CaCO_3$)	Sulfate, dissolved	Chloride, dissolved
01-21-	8.0	7.5	3.0	4.1	0.2	0.5	0.5	139	114	--	10	0.4
02-09-	7.2	7.5	4.9	3.9	.2	.4	.5	143	117	--	11	.4
03-03-	8.4	7.2	4.5	4.1	.2	.5	.5	142	116	--	10	.5
04-05-	7.5	7.6	4.4	4.4	.2	.4	.5	151	124	116	9.7	.5
05-14-	7.3	7.2	3.8	4.0	.2	.5	.6	124	102	108	11	.4
05-25-	4.8	3.6	3.6	3.5	.2	.5	.3	65	54	59	5.0	.5
06-08-	4.5	4.0	3.4	3.3	.2	.5	.5	74	61	63	4.3	.3
06-22-	6.8	2.2	3.3	2.6	.2	1.2	.3	46	38	40	2.4	.1
07-13-	2.8	2.2	3.2	3.1	.2	5.5	.3	45	37	38	2.6	.5
08-10-	4.7	4.4	3.8	4.0	.2	.4	.4	82	67	68	5.7	.2
09-13-	6.2	5.5	4.3	3.9	.2	.4	.4	--	--	85	7.4	E.2

Appendix D. *Analysis of water samples collected at U.S. Geological Survey gaging station 06187915, water year 1999--Continued*

Date	Fluoride, dissolved	Silica, dissolved (as SiO_2)	Dissolved solids, residue (at 180°C)	Dissolved solids, sum of constituents	Dissolved solids, (tons per acre-feet)	Dissolved solids, (tons per day	Nitrogen, nitrite, dissolved	Nitrogen, No_2+No_3, dissolved	Nitrogen, ammonia, dissolved	Nitrogen, ammonia + organic, total	Nitrogen, ammonia + organic, dissolved
01-21-	<0.1	11	148	136	0.20	0.80	<0.01	0.14	0.02	<0.1	<0.1
02-09-	<.1	10	145	139	.20	1.02	<.01	.12	<.02	E.06	E.06
03-03-	<.1	9.6	144	135	.20	.70	<.01	.10	<.02	E.05	<.1
04-05-	<.1	9.2	140	140	.19	.92	<.01	<.05	.02	E.08	E.06
05-14-	<.1	9.1	130	124	.02	--	<.01	<.05	<.02	E.07	<.1
05-25-	<.1	9.2	96	70	.13	55.2	<.01	.08	<.02	.2	E.09
06-08-	<.1	10	90	77	.12	63.4	<.01	.05	<.02	.1	E.09
06-22-	<.1	8.5	40	49	.05	58.9	<.01	<.05	<.02	.4	<.1
07-13-	<.1	9.4	55	50	.07	43.7	<.01	<.05	<.02	1	<.1
08-10-	<.1	11	84	85	.11	10.2	<.01	<.05	<.02	E.06	<.1
09-13-	<.1	11	95	--	--	--	<.01	<.05	<.02	E.08	E.08

Date	Phosphorus, total	Phosphorus, dissolved	Phosphorus, ortho, dissolved	Aluminum, total recoverable	Aluminum, dissolved	Antimony, total	Antimony, dissolved	Arsenic, total	Arsenic, dissolved	Barium, dissolved	Beryllium, total recoverable	Beryllium, dissolved
01-21-	0.025	0.025	0.02	0.200	0.001	<0.001	<0.001	0.001	<0.001	0.019	<0.010	<0.001
02-09-	.025	.024	.02	.02	<.001	<.001	<.001	<.001	<.001	.018	<.010	<.001
03-03-	.026	.022	.02	E.014	<.001	<.001	<.001	.001	<.001	.017	<.010	<.001
04-05-	.021	.018	.02	.058	.002	<.001	<.001	.001	<.001	.017	<.004	<.001
05-14-	.017	.012	.01	.078	.002	<.001	<.001	<.001	<.001	.021	<.004	<.001
05-25-	.094	.034	.03	<.028	.001	<.001	<.001	<.001	<.001	.012	<.004	<.001
06-08-	.051	.029	.03	.541	.008	<.001	<.001	<.001	<.001	.014	<.004	<.001
06-22-	.34	.029	.03	4.640	.015	<.001	<.001	.004	<.001	.007	<.004	<.001
07-13-	.072	.035	.04	.600	.007	<.001	<.001	<.001	<.001	.008	<.004	<.001
08-10-	.045	.035	.03	.236	.003	<.001	<.001	<.001	.002	.013	<.004	<.001
09-13-	.034	.029	.03	.197	.002	<.001	<.001	<.001	<.001	.016	<.005	<.001

Appendix D. *Analysis of water samples collected at U.S. Geological Survey gaging station 06187915, water year 1999--Continued*

Date	Cadmium, water unfilterd total	Cadmium, dissolved	Chromium, total recoverable	Chromium, dissolved	Cobalt, total recoverable	Cobalt, dissolved	Copper, total recoverable	Copper, dissolved	Iron, total recoverable	Iron, dissolved	Lead, total recoverable
01-21-	<0.001	<0.001	<0.001	0.002	<0.001	<0.001	<0.010	<0.001	0.060	<0.010	<0.001
02-09-	<.001	<.001	<.001	.004	<.001	<.001	.010	<.001	.050	<.010	<.001
03-03-	<.001	<.001	<.001	.007	<.001	<.001	<.010	<.001	.050	<.010	<.001
04-05-	<.001	<.001	<.001	<.001	<.001	<.001	<.012	<.001	.084	<.010	<.001
05-14-	<.001	<.001	<.001	<.001	<.001	<.001	<.010	<.001	.198	<.010	<.001
05-25-	<.001	<.001	.0015	<.001	.002	<.001	E.011	.002	1.730	.016	.001
06-08-	<.001	<.001	.0013	--	<.001	<.001	<.012	.001	.842	.015	<.001
06-22-	<.001	<.001	.0048	<.001	.005	<.001	.022	.002	6.260	.012	.013
07-13-	<.001	<.001	<.001	<.001	<.001	<.001	<.012	<.001	.753	E.009	<.001
08-10-	<.001	<.001	<.001	<.001	<.001	<.001	<.012	<.001	.395	<.010	<.001
09-13-	<.001	<.001	<.001	<.001	<.001	<.001	<.020	<.001	.445	<.010	<.001

Date	Lead, dissolved	Lithium, total recoverable	Manganese, total recoverable	Manganese, dissolved	Mercury, total recoverable	Mercury, dissolved	Molybdenum, total recoverable	Molybdenum, dissolve	Nickel, total recoverable	Nickel, dissolved	Selenium, total
01-21-	<0.001	<0.010	<0.010	<0.001	<0.0001	--	0.0015	0.001	<0.001	<0.001	0.001
02-09-	<.001	<.010	<.010	<.001	<.0001	<.0001	.0016	.001	<.001	<.001	<.001
03-03-	<.001	<.010	<.010	<.001	<.0001	<.0001	.0014	<.001	<.001	.001	<.001
04-05-	<.001	<.012	<.003	<.001	<.0001	<.0001	.0014	.001	<.001	<.001	<.001
05-14-	<.001	<.016	.0068	.003	<.0001	<.0001	<.001	<.001	<.001	<.001	<.001
05-25-	<.001	<.012	.0377	.003	.0001	<.0001	<.001	<.001	.005	<.001	<.001
06-08-	<.001	<.012	.0180	.002	<.0001	<.0001	<.001	<.001	.002	<.001	<.001
06-22-	<.001	<.012	.210	.003	.0001	<.0001	<.001	<.001	.013	<.001	<.001
07-13-	<.001	<.012	<.0151	.001	<.0002	<.0001	<.001	<.001	..002	<.001	<.001
08-10-	<.001	<.012	<.0070	.002	<.0001	<.0001	<.001	<.001	<.001	.001	<.001
09-13-	<.001	<.007	<.0056	.002	<.0001	<.0001	<.0016	<.001	<.001	<.001	<.001

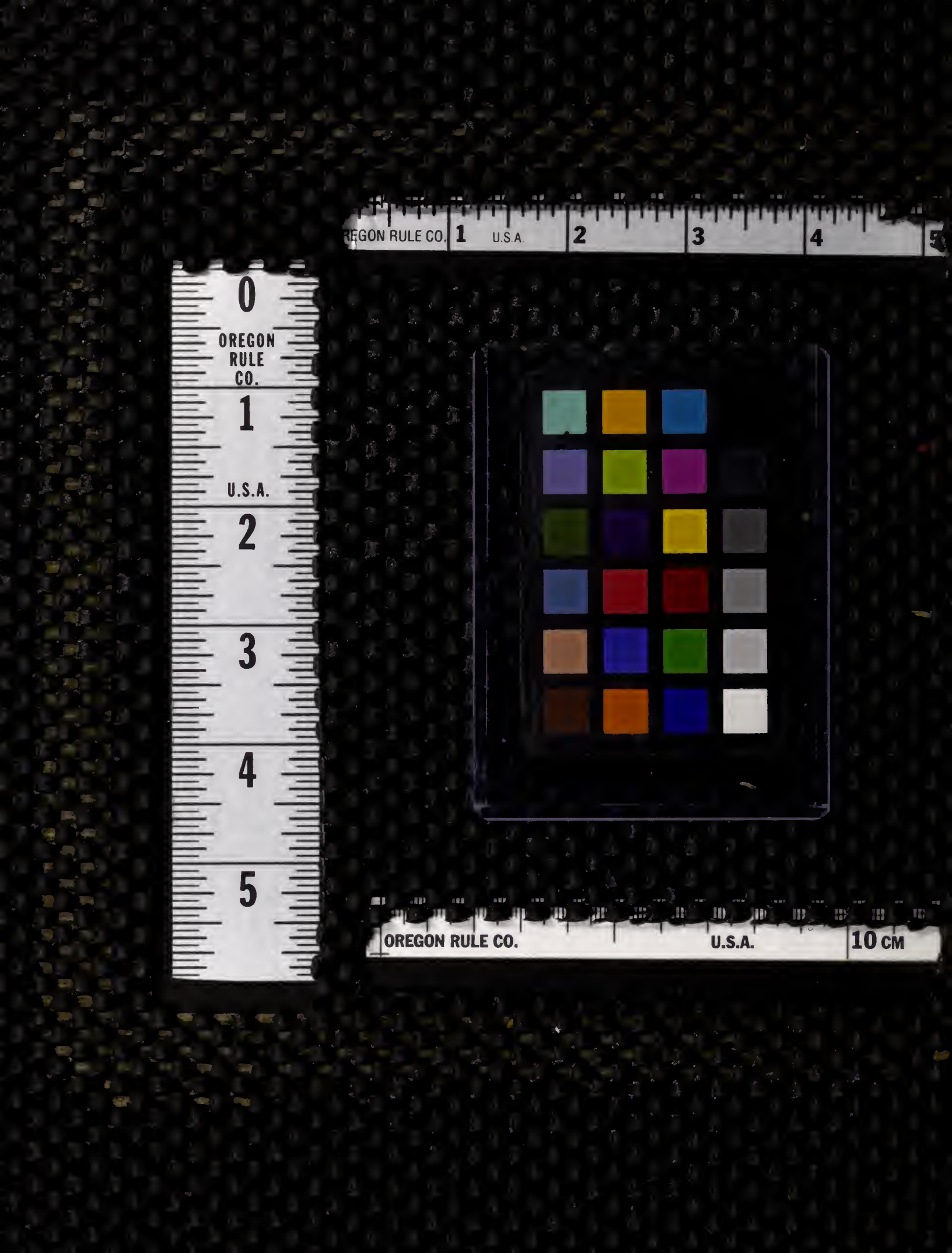
Appendix D. *Analysis of water samples collected at U.S. Geological Survey gaging station 06187915, water year 1999--Continued*

Date	Selenium, dissolved	Silver, total recoverable	Silver, dissolved	Strontium, total recoverable	Zinc, total recoverable	Zinc, dissolved	Uranium natural, dissolved	Carbon, organic dissolved	Carbon, organic suspended	Sediment, suspended	Sediment discharge, suspended (tons/day)
01-21-	<0.001	<0.001	<0.001	0.100	<0.010	<0.001	<0.001	0.6	0.2	1	0.01
02-09-	.001	<.001	<.001	.140	<.010	.001	<.001	.7	<.2	1	.01
03-03-	<.001	<.001	<.001	.130	<.010	.001	<.001	.6	<.2	1	.00
04-05-	<.001	<.001	<.001	.134	E.0311	<.001	<.001	.7	.2	1	.01
05-14-	<.001	<.001	<.001	.117	E.0302	<.001	<.001	1.2	<.2	1	--
05-25-	<.001	<.001	<.001	.0686	<.040	<.001	<.001	2.2	.6	55	32
06-08-	<.001	<.001	<.001	.0650	<.040	.001	<.001	2.3	.3	23	16
06-22-	<.001	<.001	<.001	.0759	E.0233	<.001	<.001	1.6	1.3	289	425
07-13-	<.001	<.001	<.001	.0413	<.040	<.001	<.001	.9	<.2	27	21
08-10-	.001	<.001	<.001	.0715	<.040	.002	<.001	.7	.2	3	.36
09-13-	<.001	<.001	<.001	.0884	<.031	<.001	<.001	.9	<.2	2	.10

☆ U.S. GOVERNMENT PRINTING OFFICE: 2001 — 773-084 / 49001 Region No. 8

Boughton — Metal Loading in Soda Butte Creek Upstream of Yellowstone National Park, Montana and Wyoming — WRIR 01-4170

ISBN 0-607-98040-0


REGON RULE CO.
1
U.S.A.
2
3
4
0
OREGON
RULE
CO.
1
U.S.A.
2
3
4
5
OREGON RULE CO.
U.S.A.
10 CM